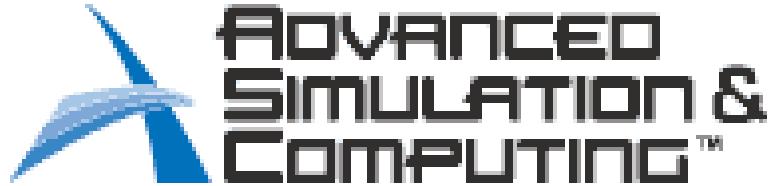




Sandia
National
Laboratories



Joint U.S. Russia Conference
on Advances in Materials Science
Prague, August 30 - September 4, 2009

Density and nonideality effects
in plasmas

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Physics and Technology*



Contents

Introduction.

1. Warm dense matter.
2. Density effects.
3. Nonideality effects.

Conclusions.

1. Warm dense matter

Sources of generation

Femtosecond Lasers

Sofia 2009, XXXVII EPS Conference on Plasma Physics

Nanosecond exploding wires

G.E. Norman, V.V. Stegailov, A.A. Valuev.

*Nanosecond Electric Explosion of Wires:
from Solid Superheating to Nonideal Plasma Formation*

Contrib. Plasma Phys., 43, 384 (2003)

Fast Single Ions

A.V.Larkin, I.V.Morozov,

G.E.Norman, S.A. Pikuz Jr., I.Yu.Skobelev

Solid-density plasma nanochannel

generated by a fast single ion in condensed matter

Physical Review E 79, 036407 (13 pp) (2009)

Name variants (Sofia 2009)

Excited state of warm dense matter

or

Exotic state of warm dense matter

or

Novel form of warm dense matter

or

New form of plasma

Similarity:

transient but steady (quasi-stationary for a short time) state of non-equilibrium, uniform plasmas (no reference to non-ideality, both ***strongly and weakly*** coupled plasmas can be formed)

lifetime limiting processes:

electron-phonon exchange, recombination, collisional electron cooling.

solid state density, two temperatures:

electron temperature about *tens* eV,

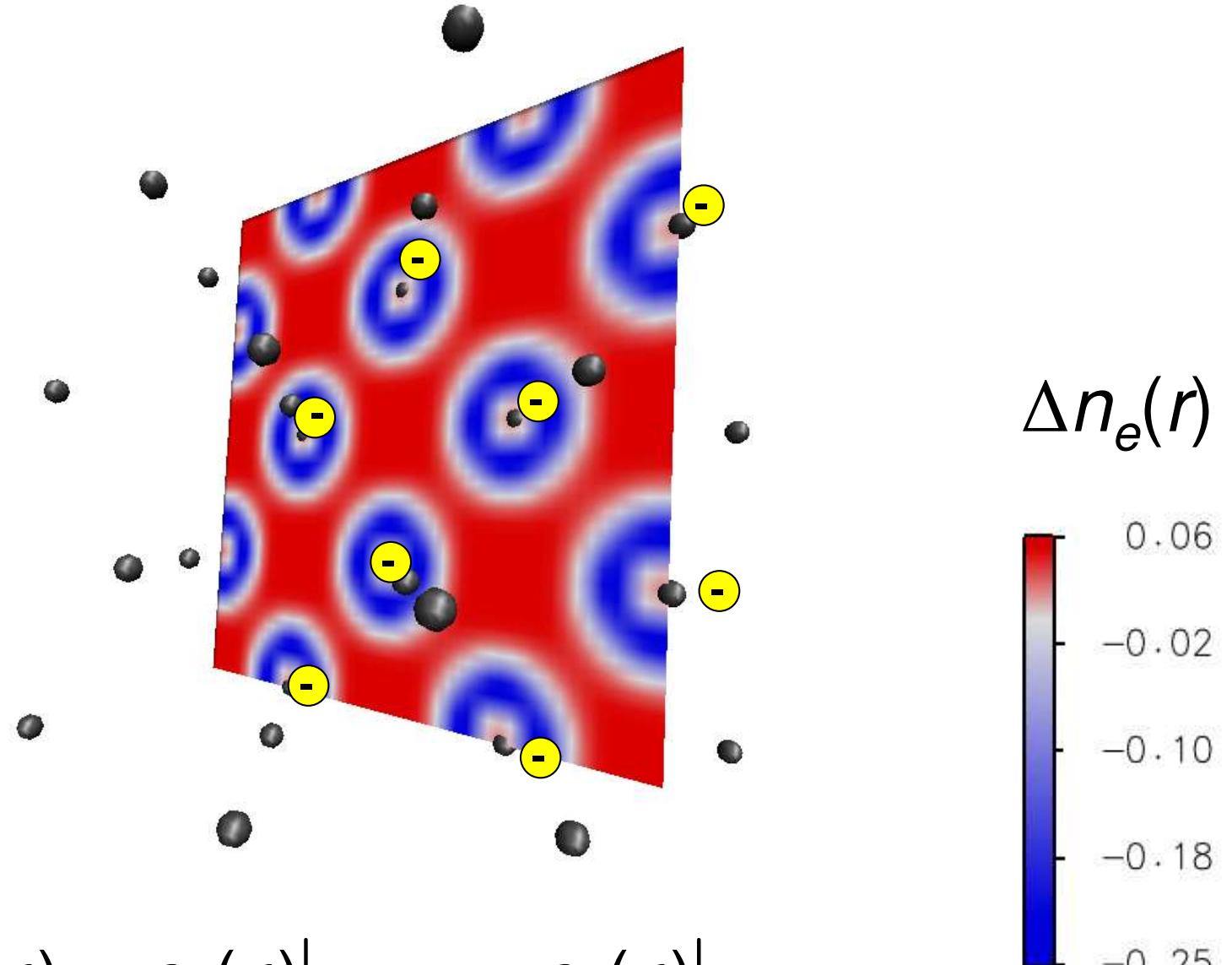
cold ions keep original crystallographic positions,

electron band structure and phonon dispersion are changed,

spectral line spectra are emitted by ion cores embedded in plasma environment which influences the spectra strongly,

Redistribution of the electron density after the electron temperature increase

f.c.c. Au



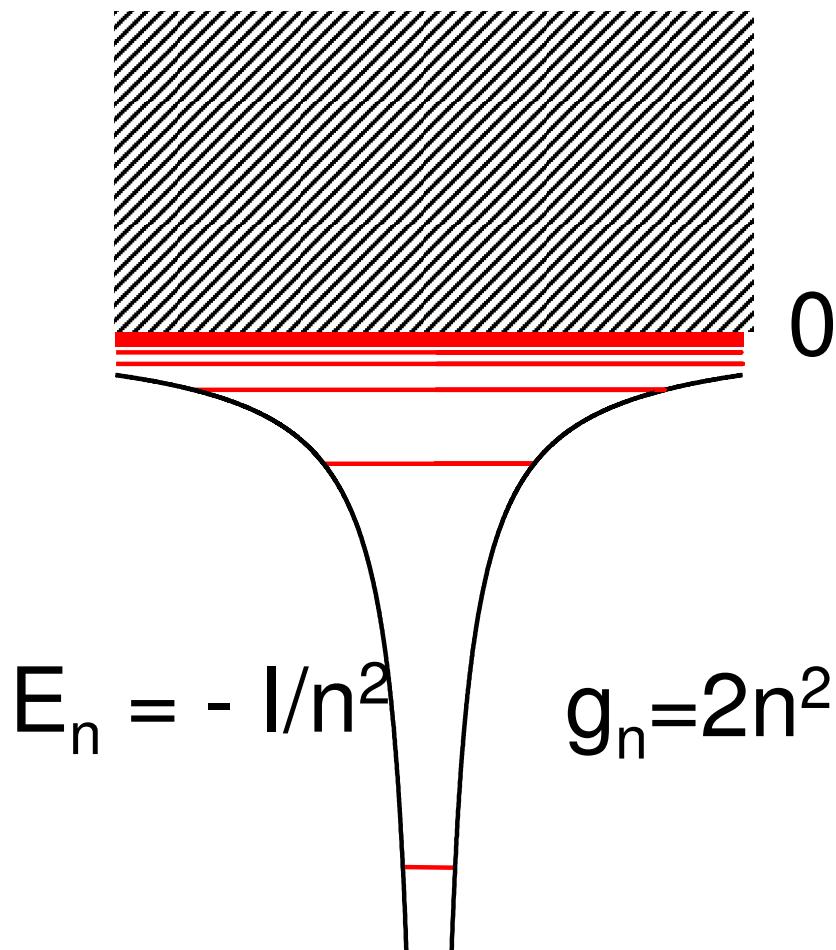
2. Density effects

- 2.1. Heart of the problem
- 2.2. Approach idea
- 2.3. Density of pair electron states at the ionization limit
- 2.4. Density of excited electron states at the ionization limit
- 2.5. Temperature independence
- 2.6. Disappearance of spectral lines

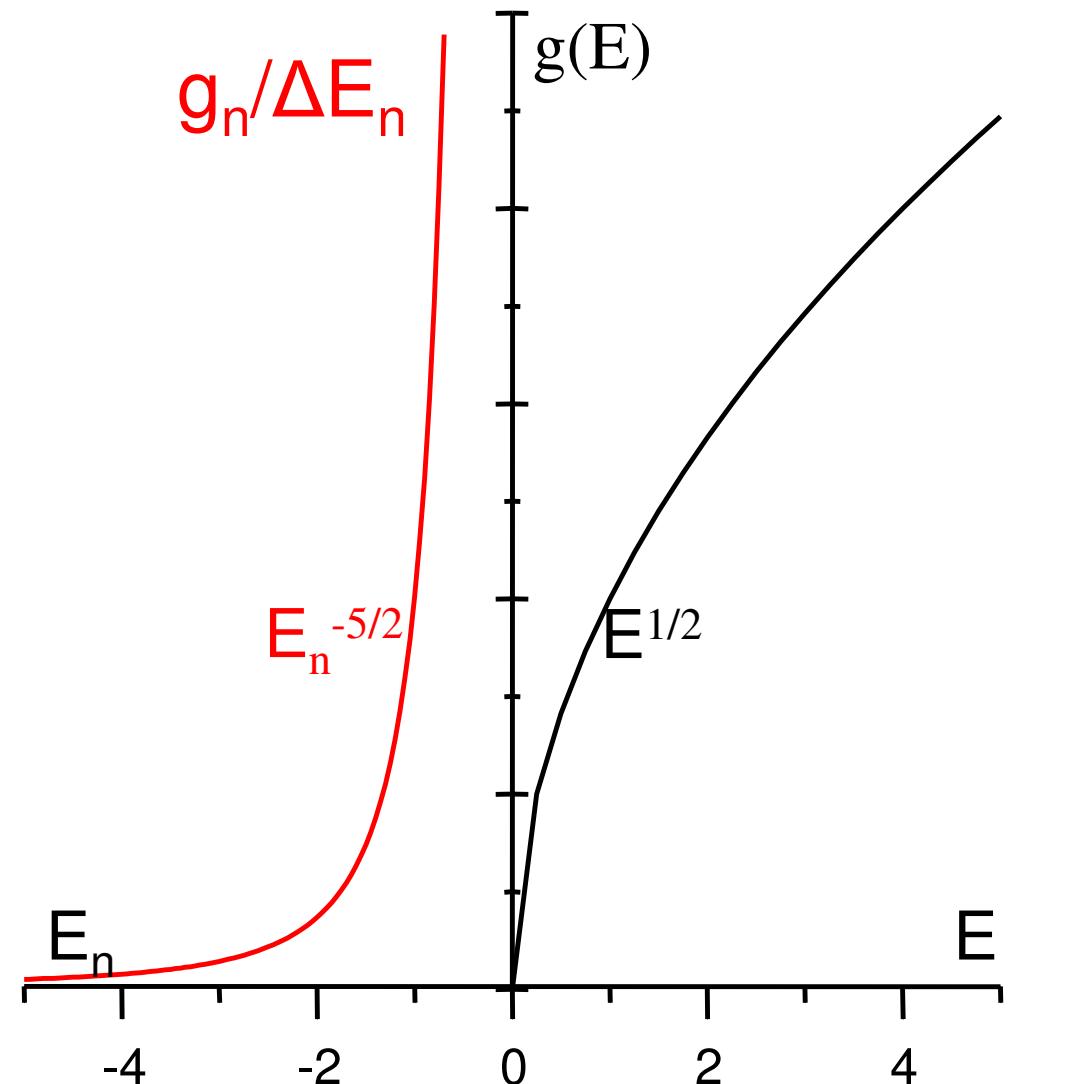
2.1. Heart of the problem

Electron states in plasmas

hydrogen atom



1. Restriction of excited states of atoms



2. Transition from bound pair excited states to collective excitations of free electrons

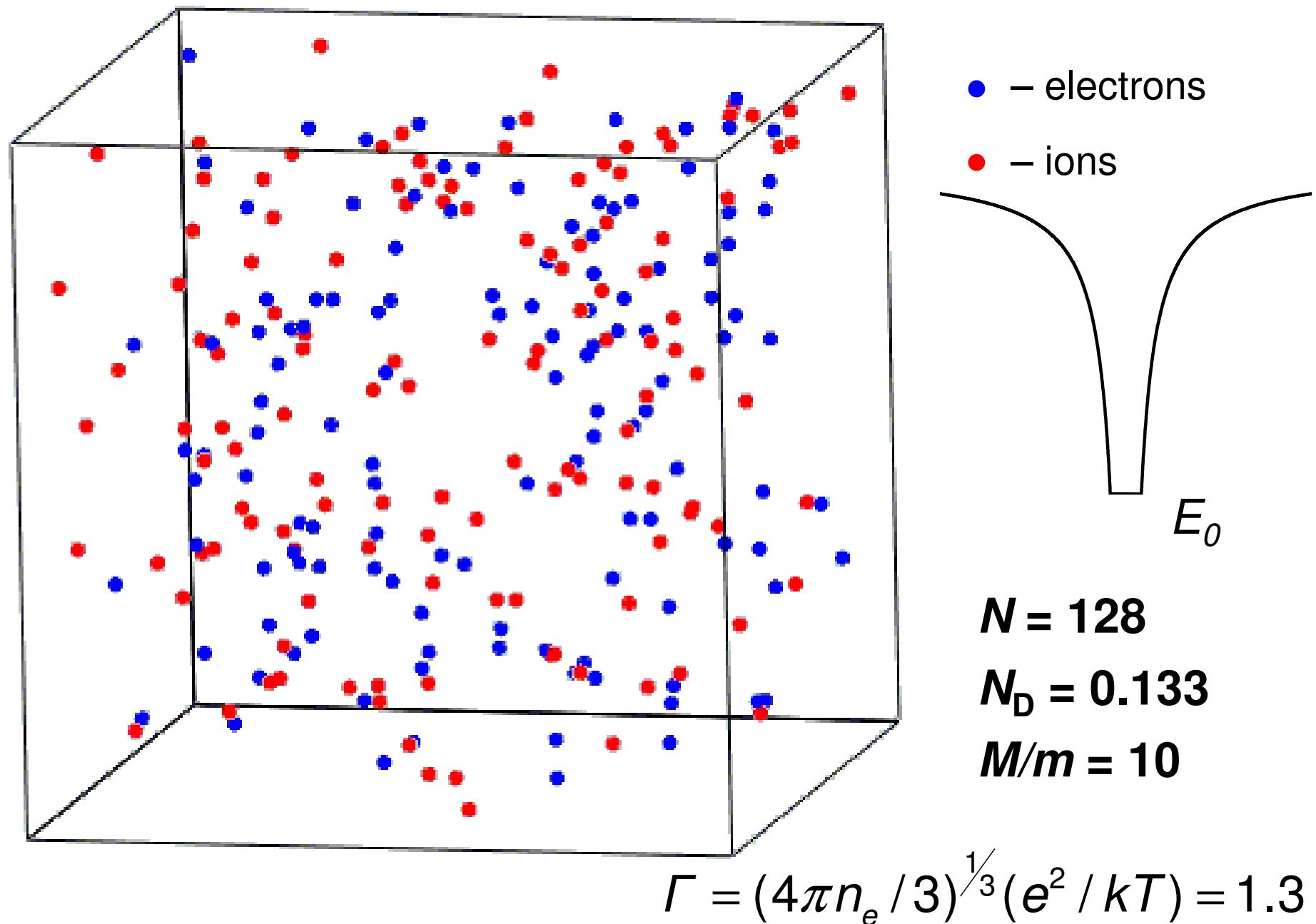
Two problems

1. Restriction of the number of excited states.
It was treated a great number of times since 1913 by Bohr, Fermi, Plank, Brillouin, Larkin, **Ebeling, Kraeft, Starostin, Röpke, Alastuey, Gryaznov, Iosilevski, et al**
2. Crossover from bound pair electron-ion excited states to collective excitations of free electrons.

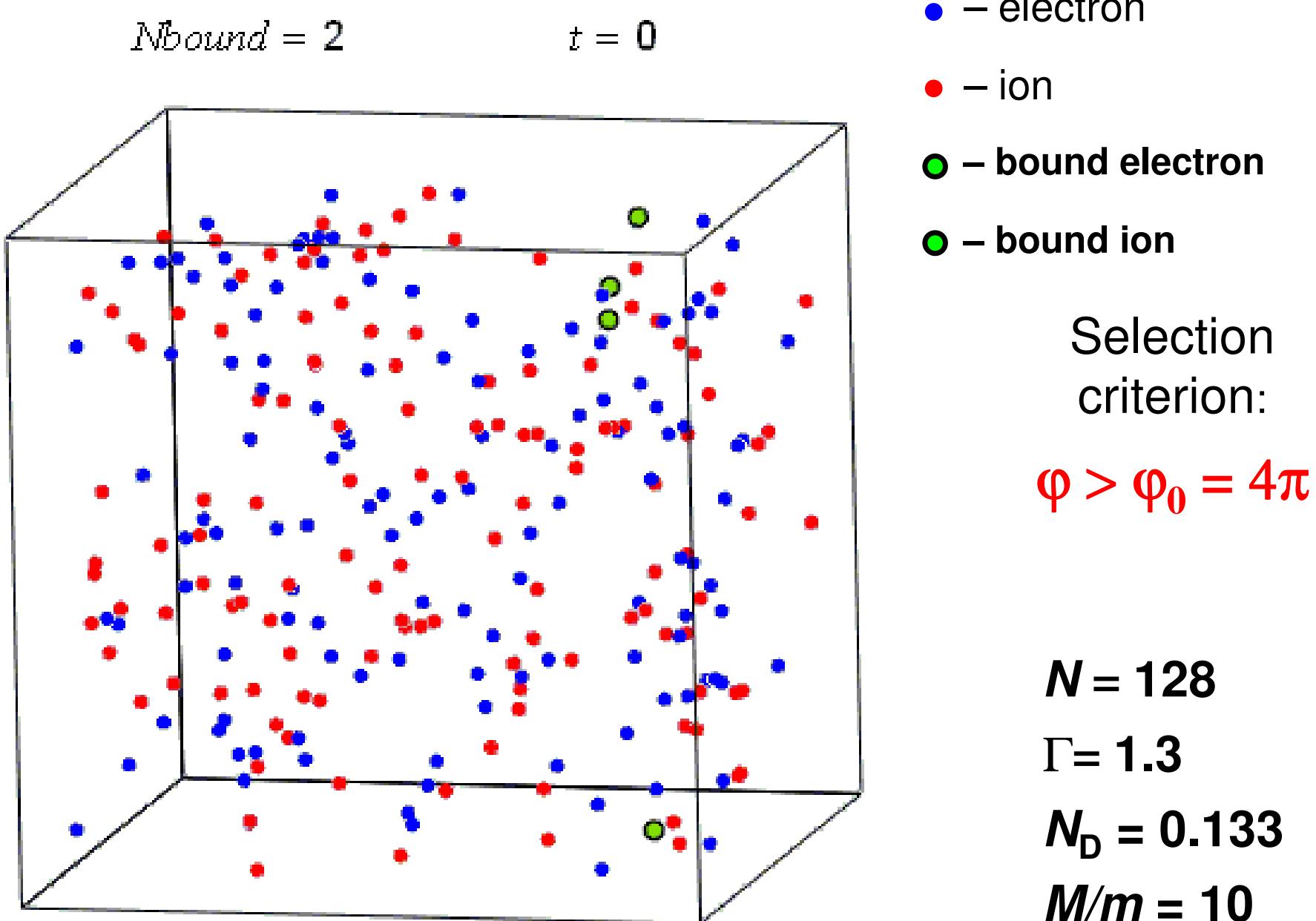
Our idea of the crossover is **to bridge**:
excited atoms – pair fluctuations – triple
fluctuations – multiple fluctuations – collective
fluctuations or excitations (plasma waves)

2.2. Approach idea

Visualization of moving particles in MD-cell



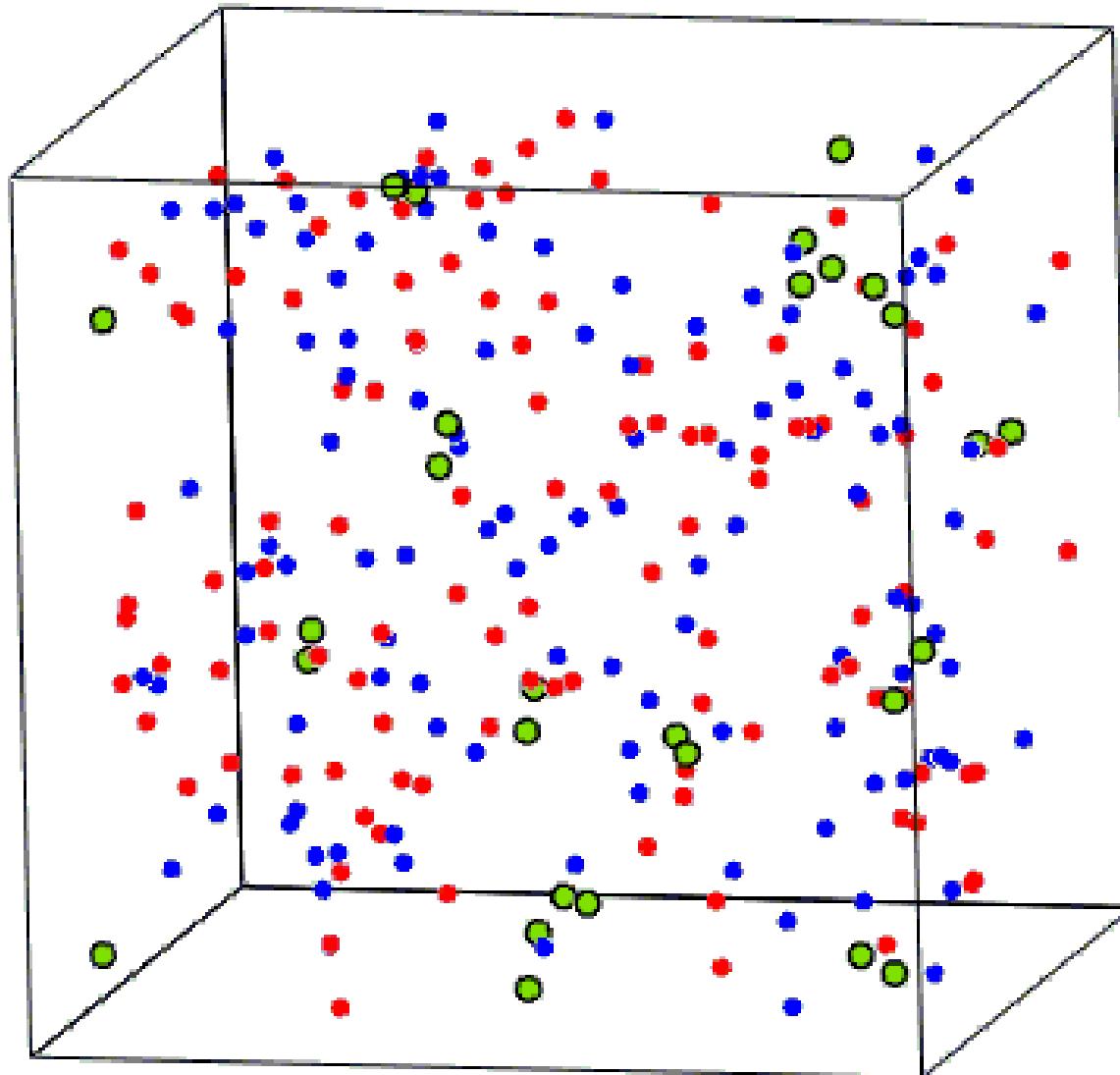
Pair transient bound state visualization



Pair transient bound state visualization

$N_{\text{bound}} = 14$

$t = 0$



- – electron
- – ion
- – bound electron
- – bound ion

Selection
criterion:

$$\varphi > \varphi_0 = 2\pi$$

$$N = 128$$

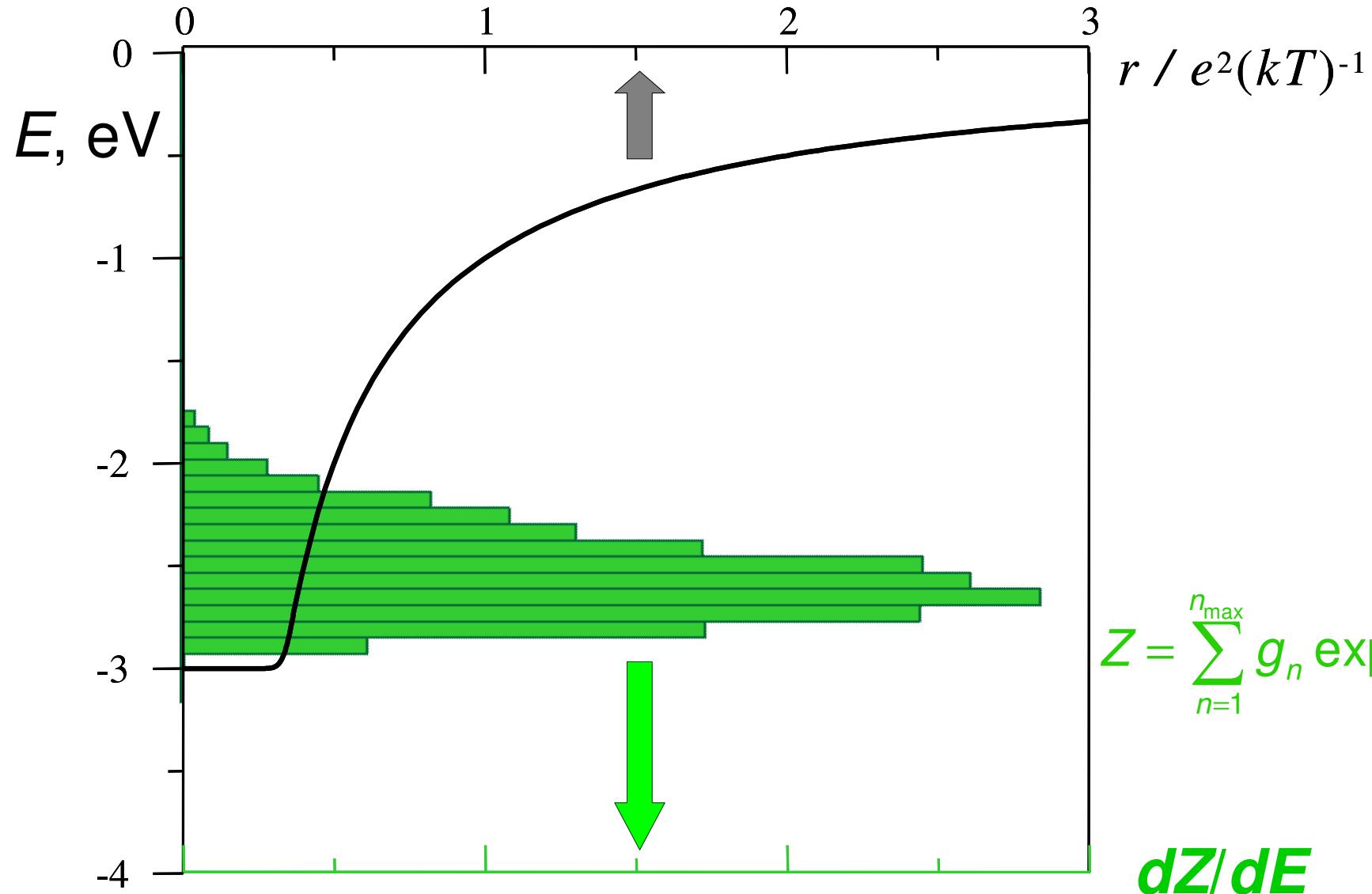
$$\Gamma = 1.3$$

$$N_D = 0.133$$

$$M/m = 10$$

2.3. Density of *pair* electron states at the ionization limit

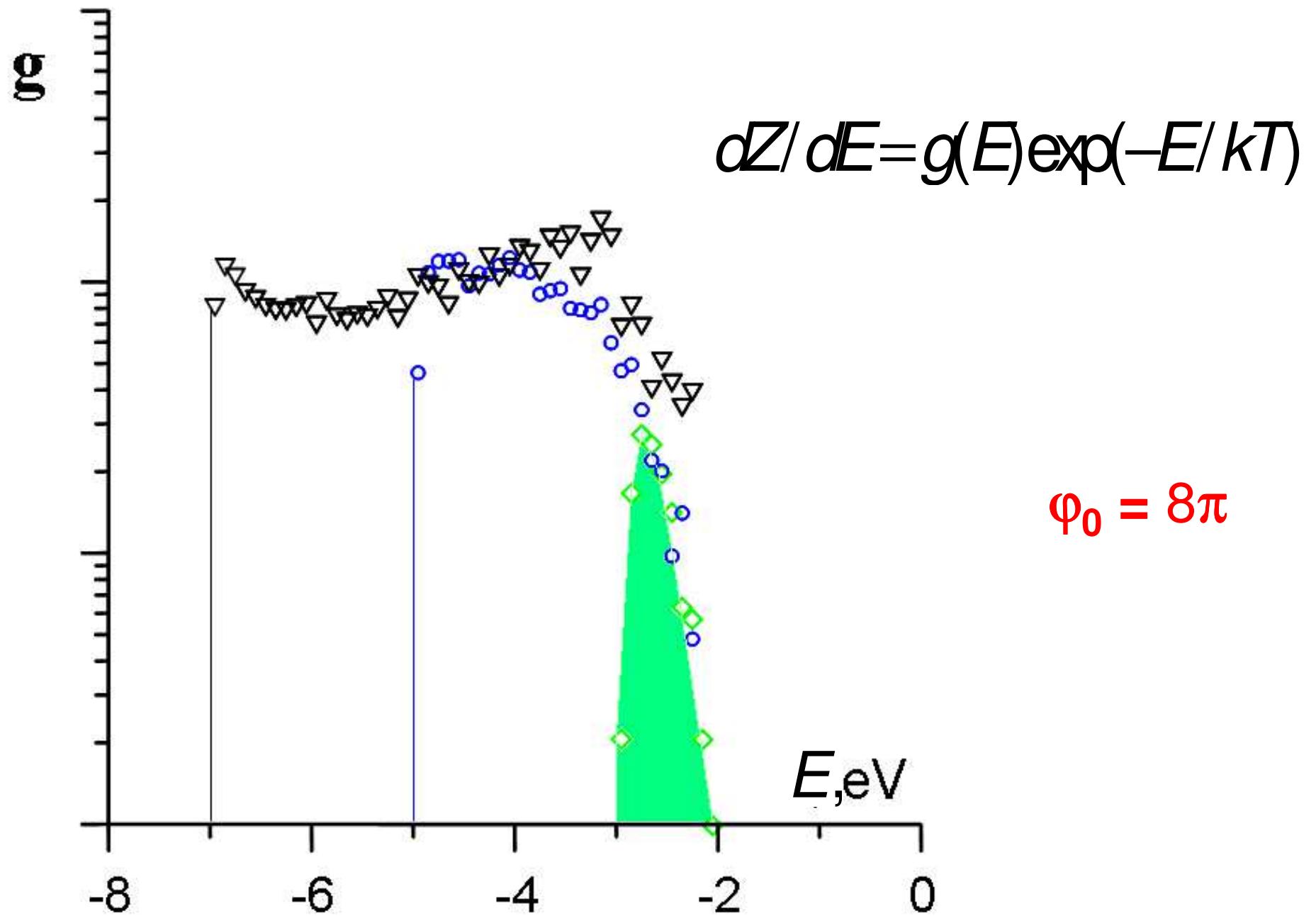
Pair state populations



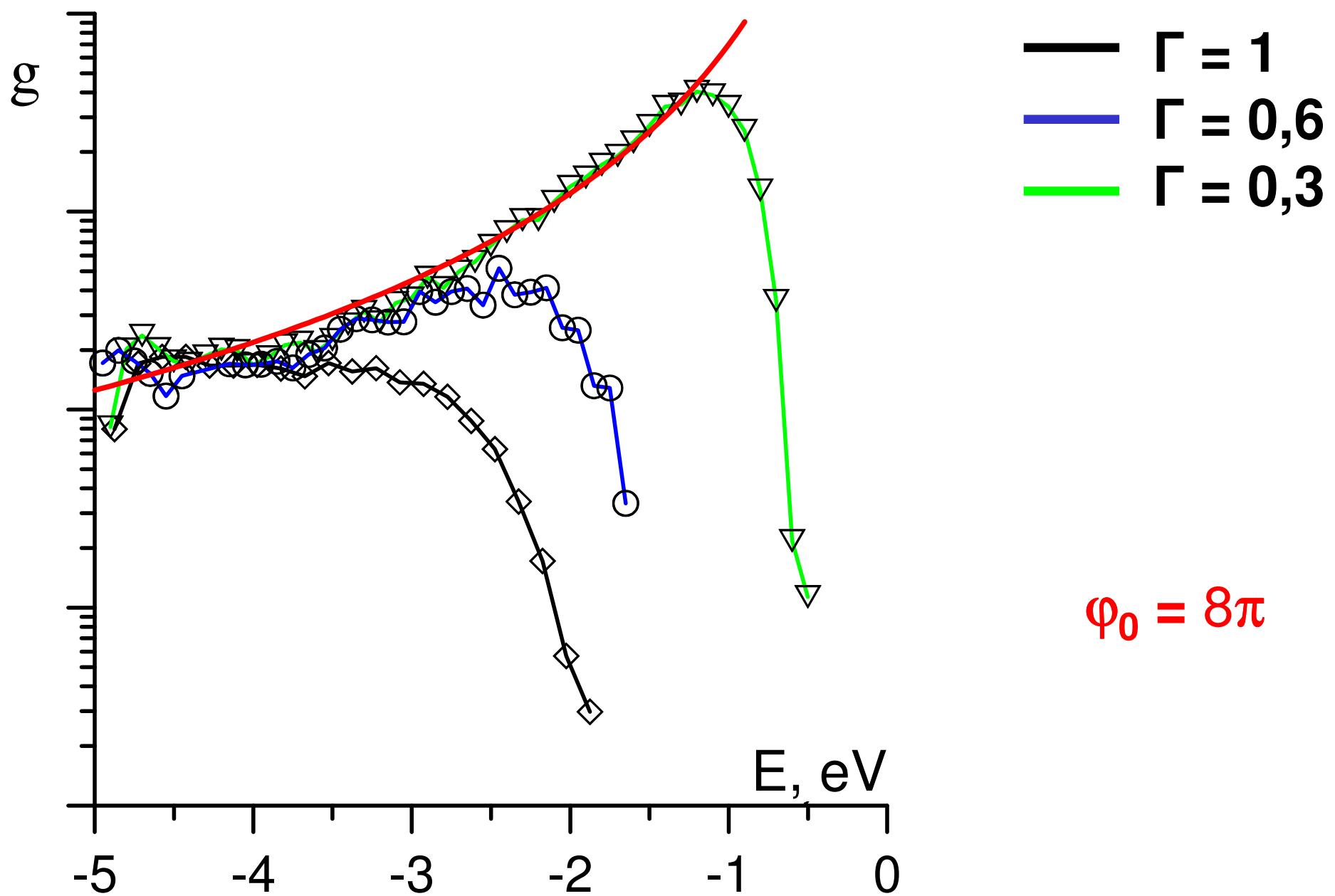
$$Z = \sum_{n=1}^{n_{\max}} g_n \exp\left(-\frac{E_n}{kT}\right)$$

dZ/dE

Density of pair states at $\Gamma = 1$

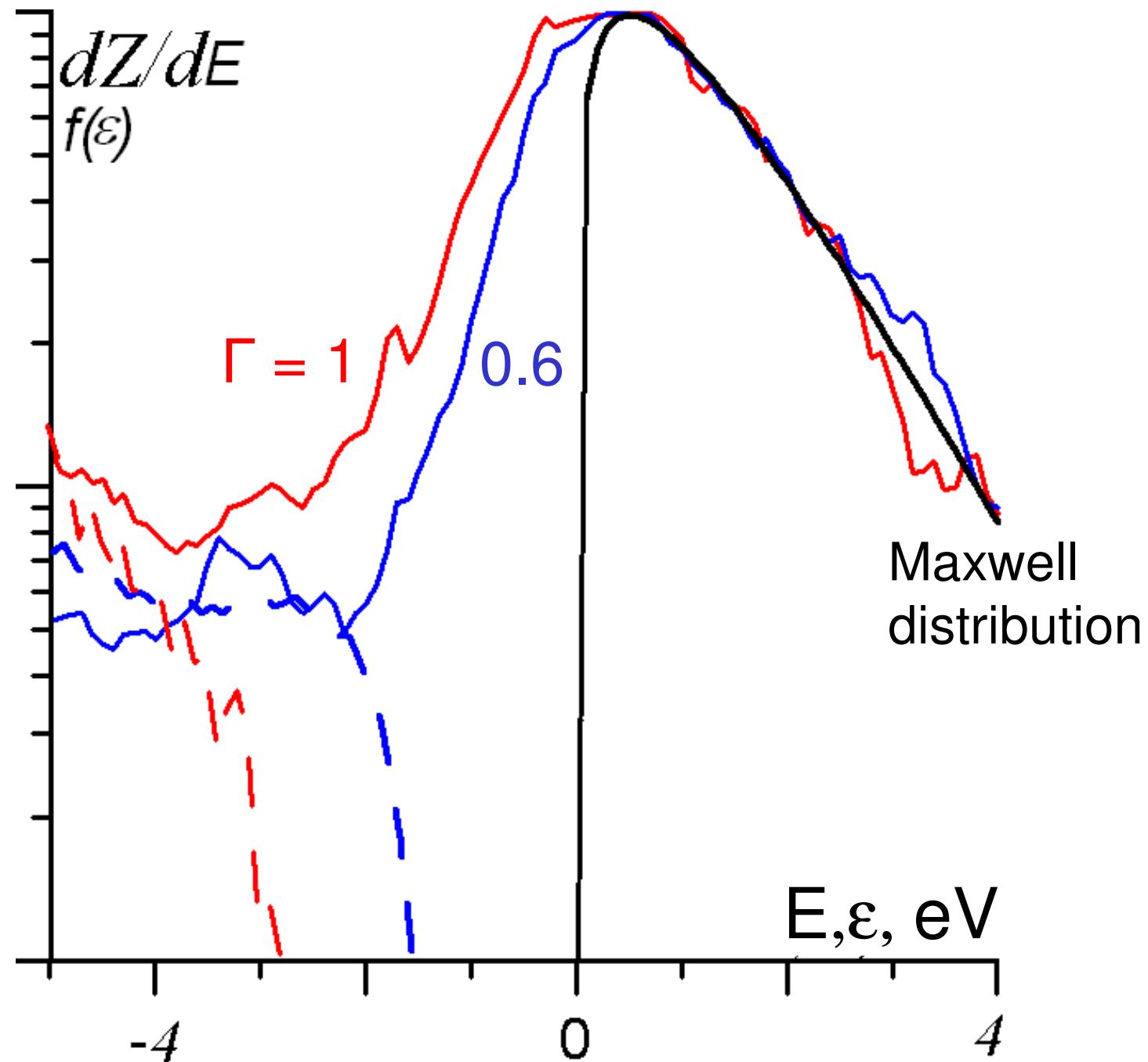


Density of pair states at different nonidealities

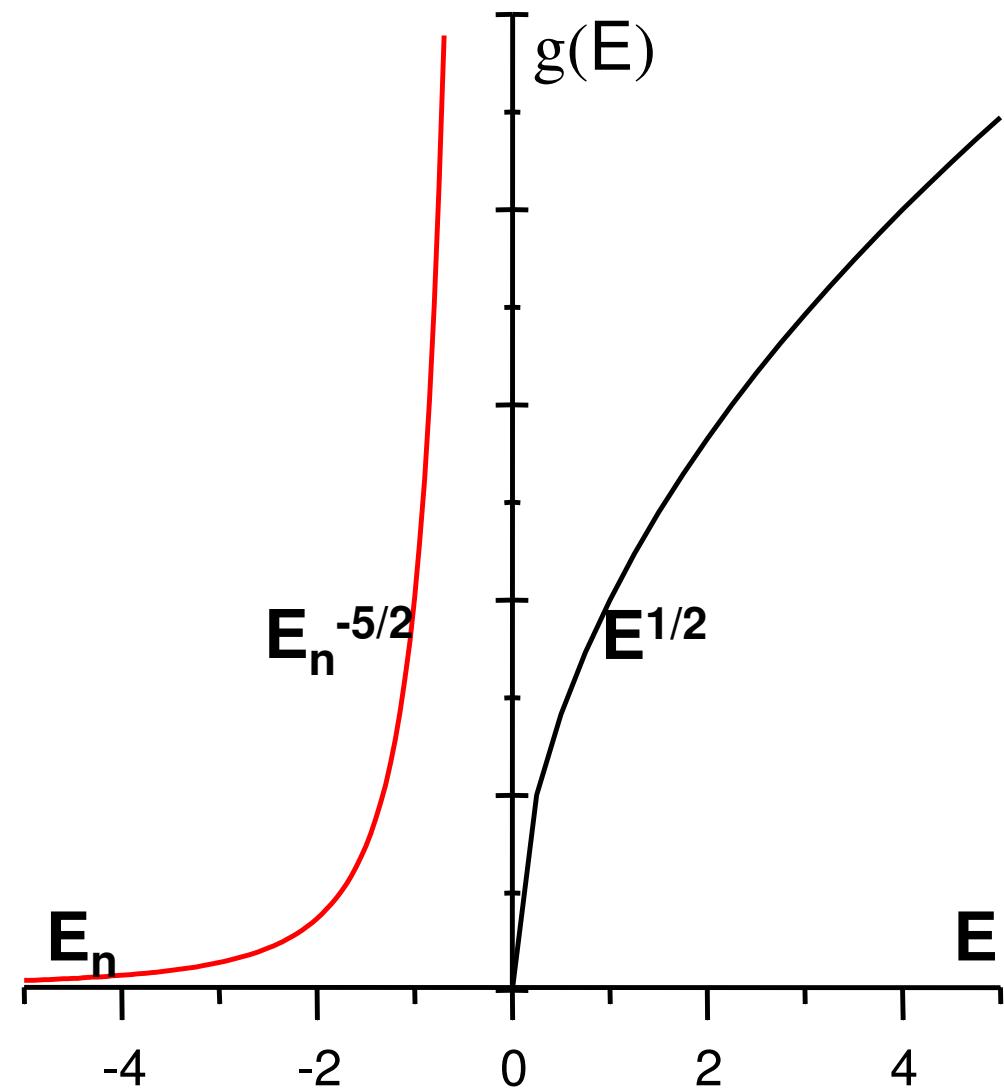
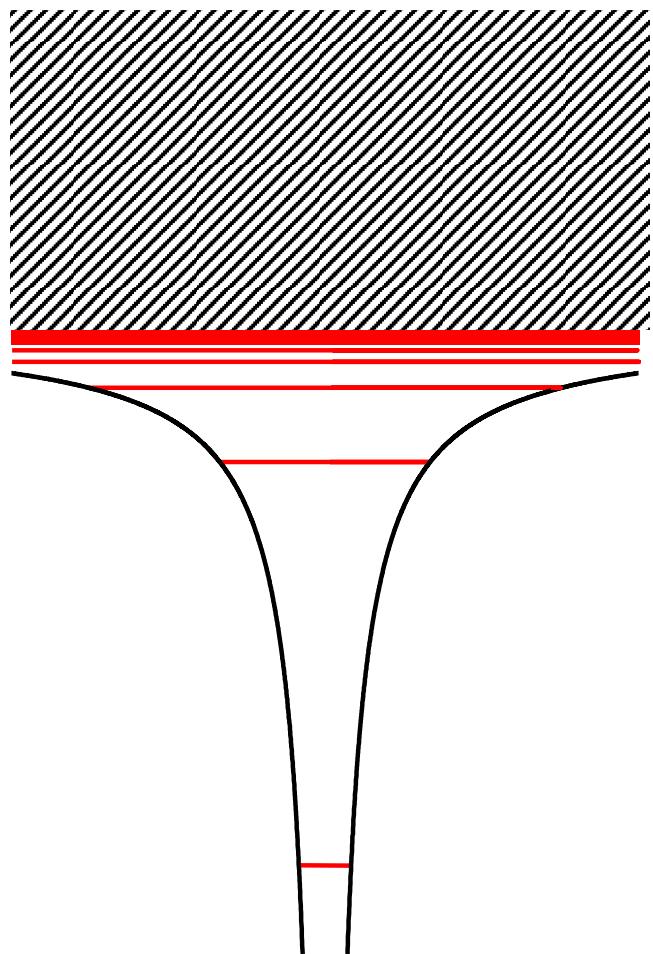


2.4. Density of *excited* electron states at the ionization limit

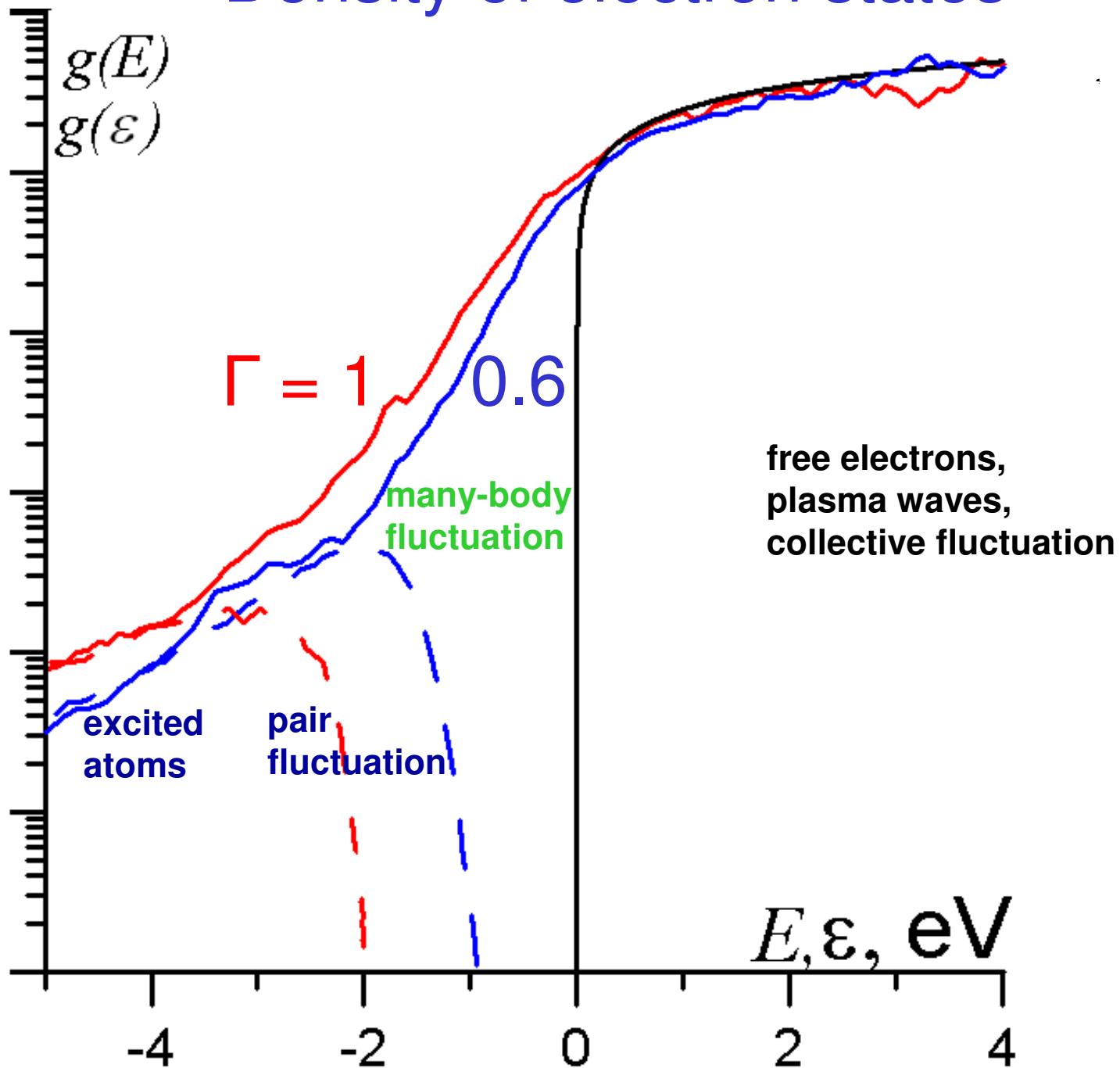
Population distributions



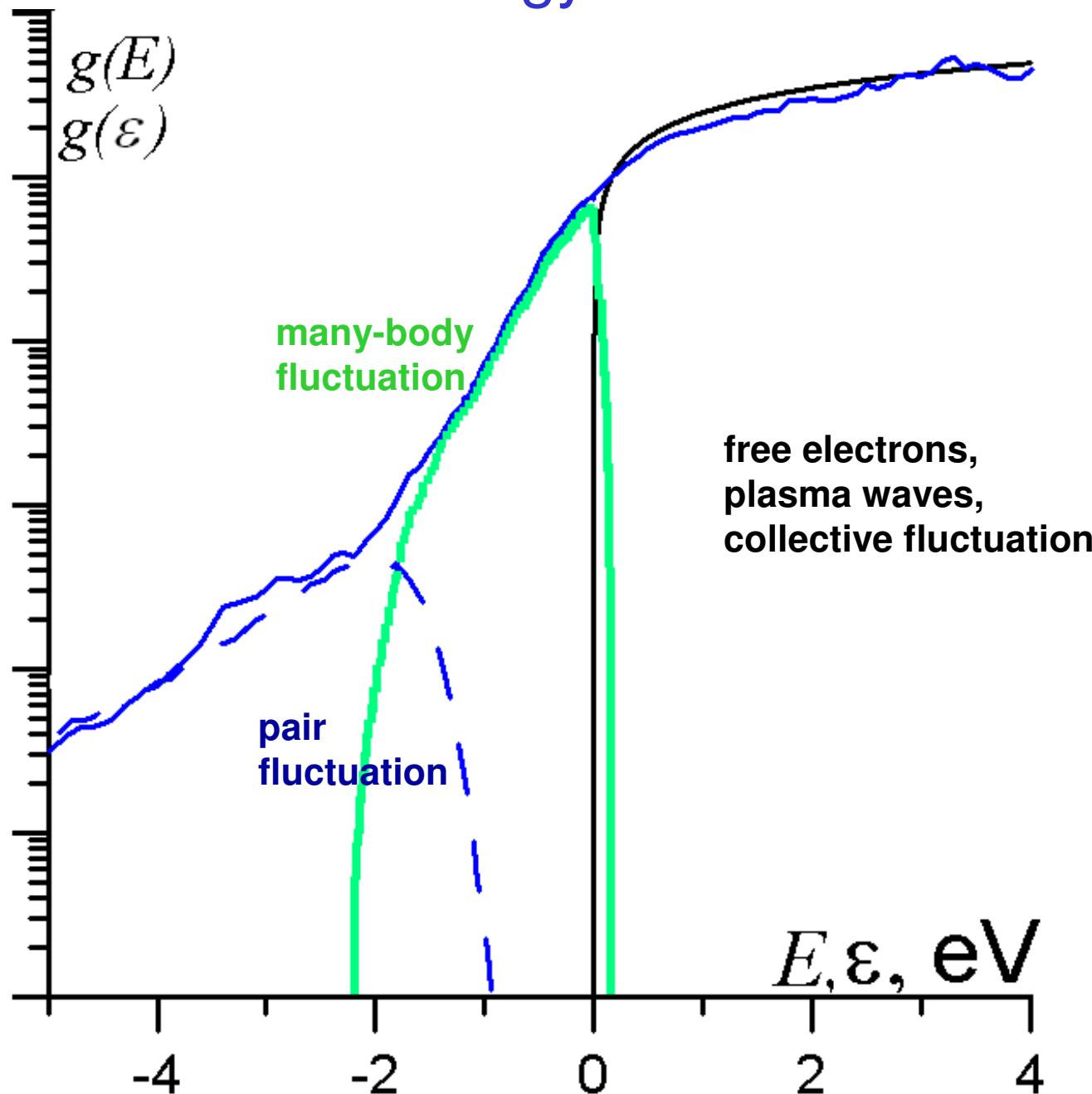
Electron states in plasmas



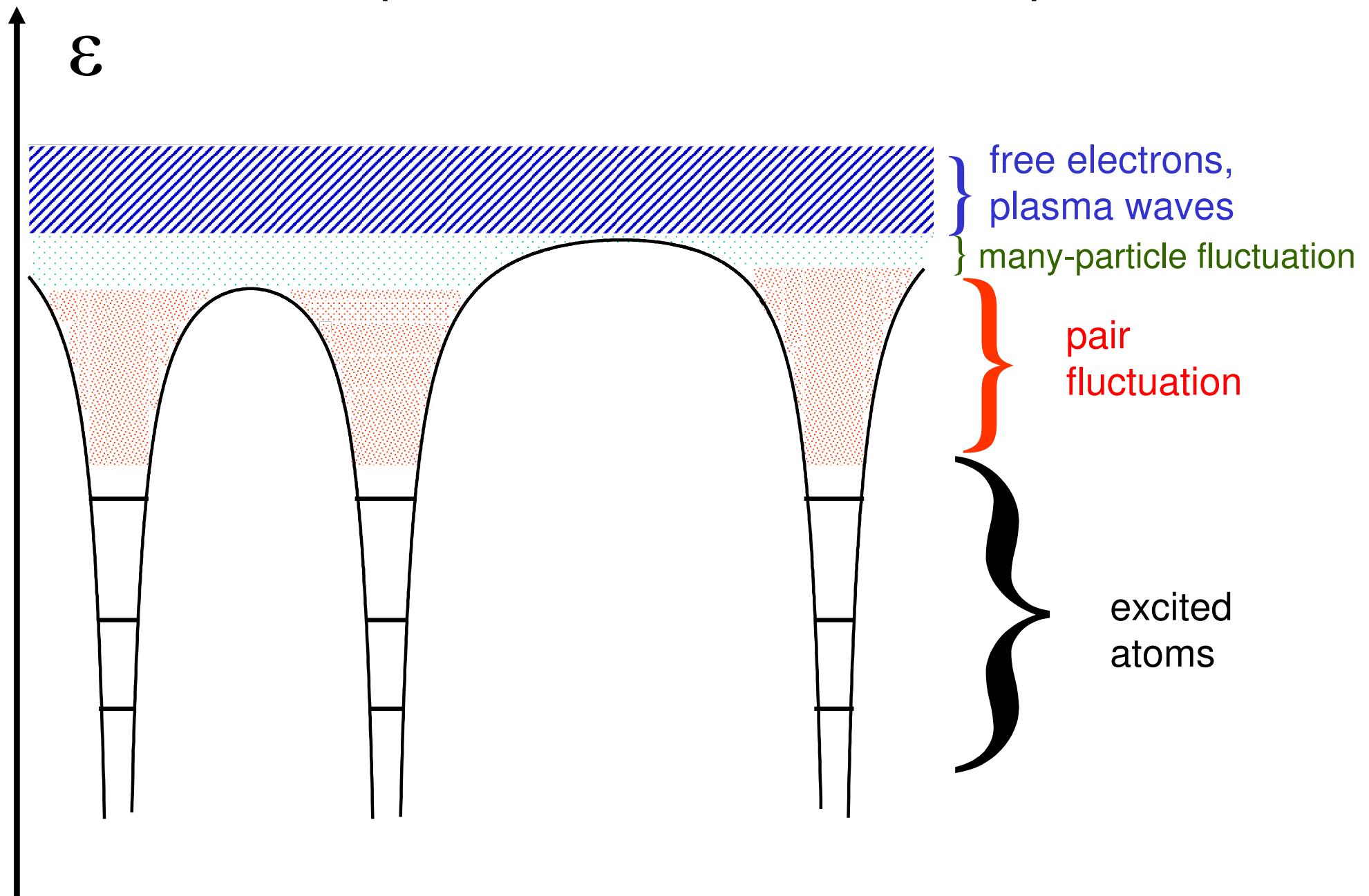
Density of electron states



Distributions of localized, free and bound states over energy at $\Gamma = 0.6$

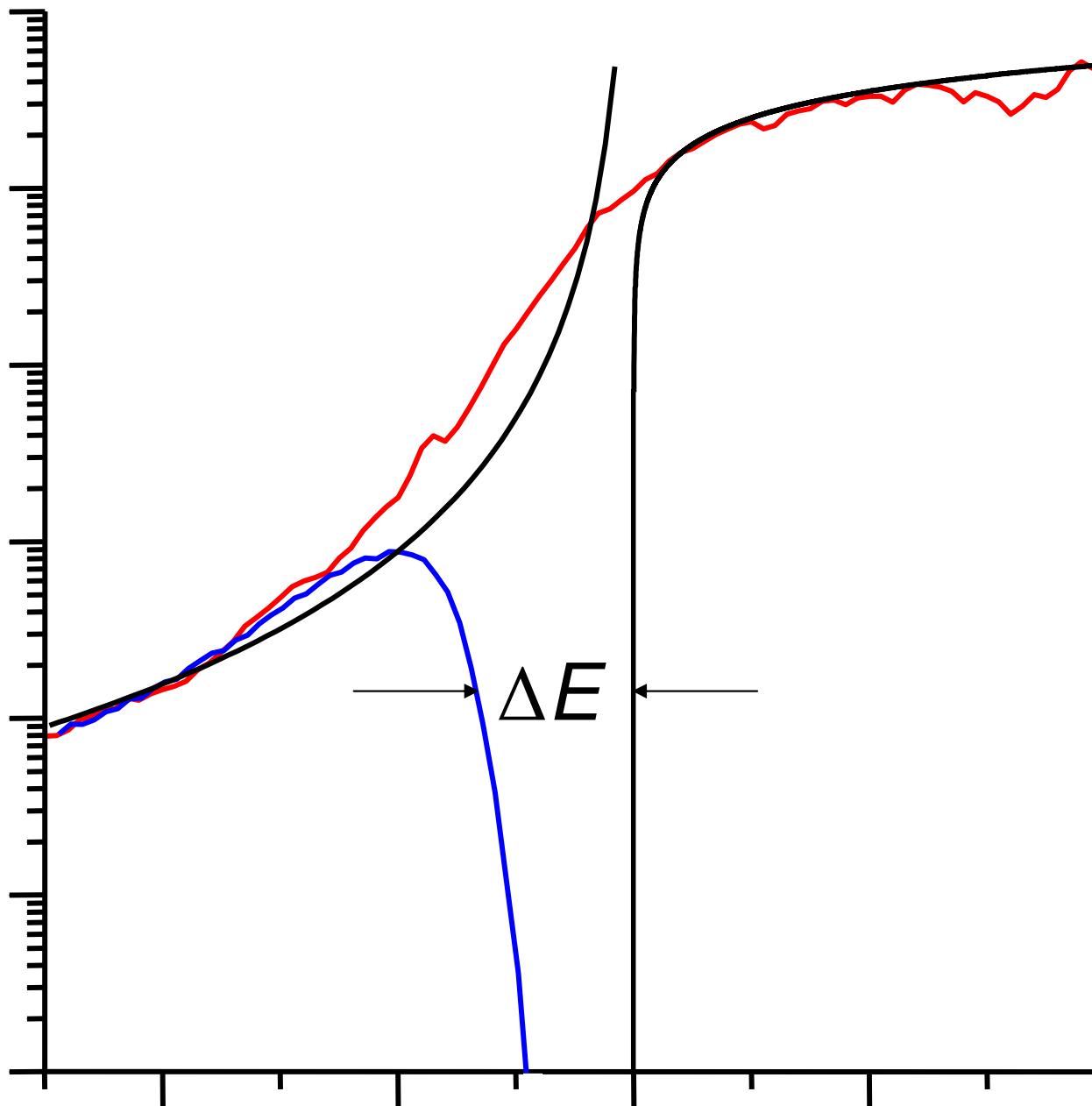


Potential profile of electron states in plasma

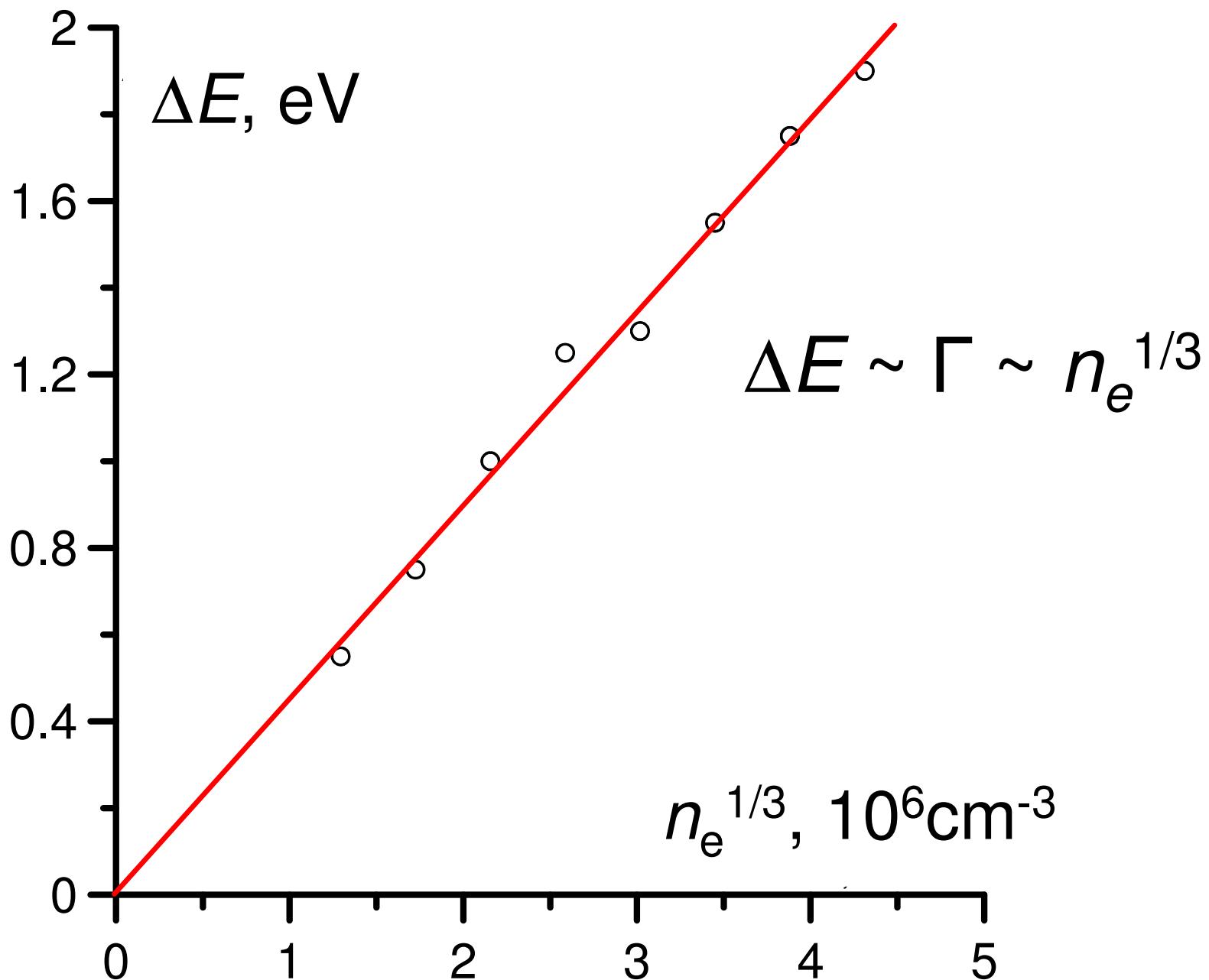


2.5. Temperature independence

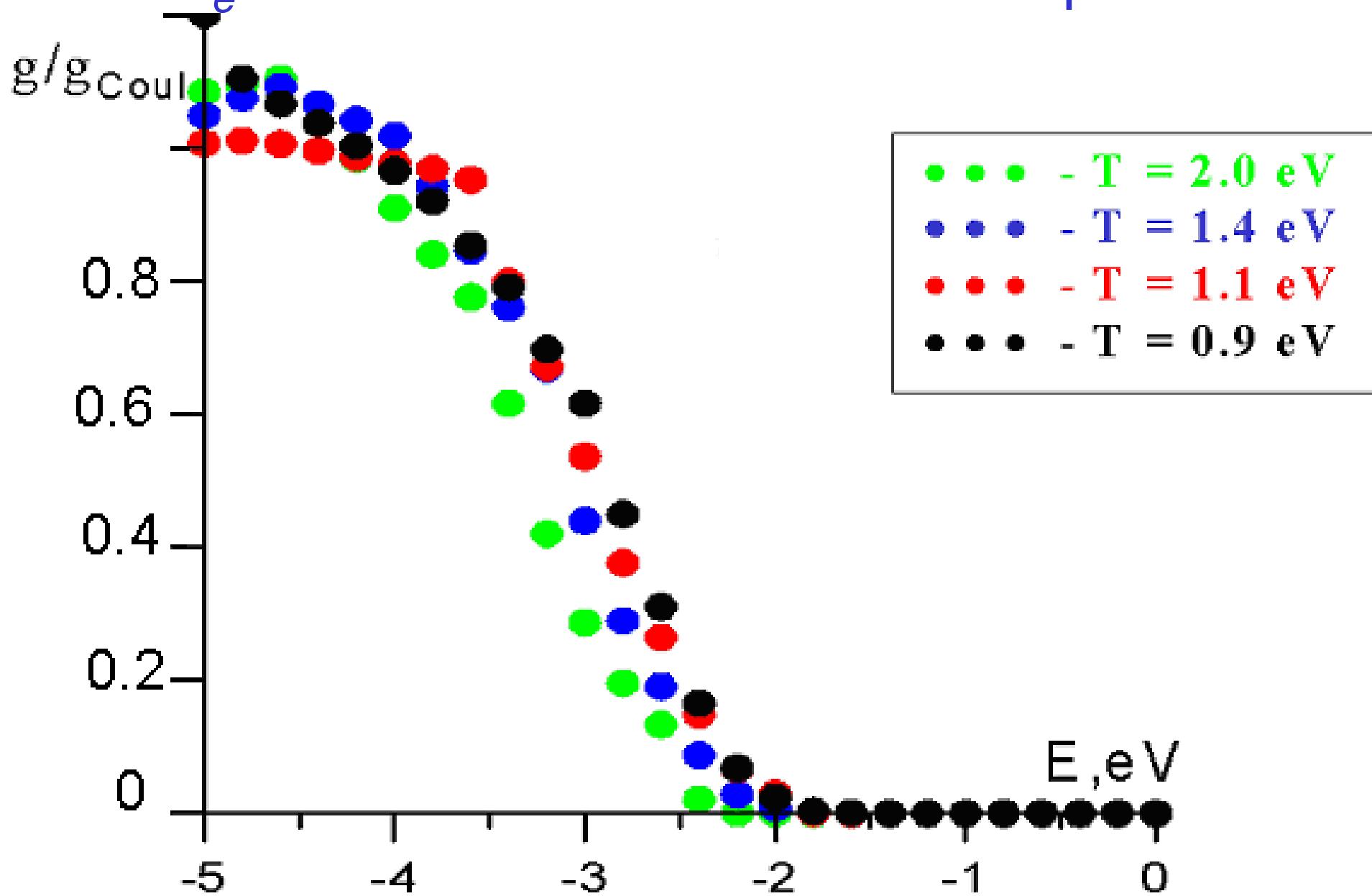
“Gap” in the spectrum



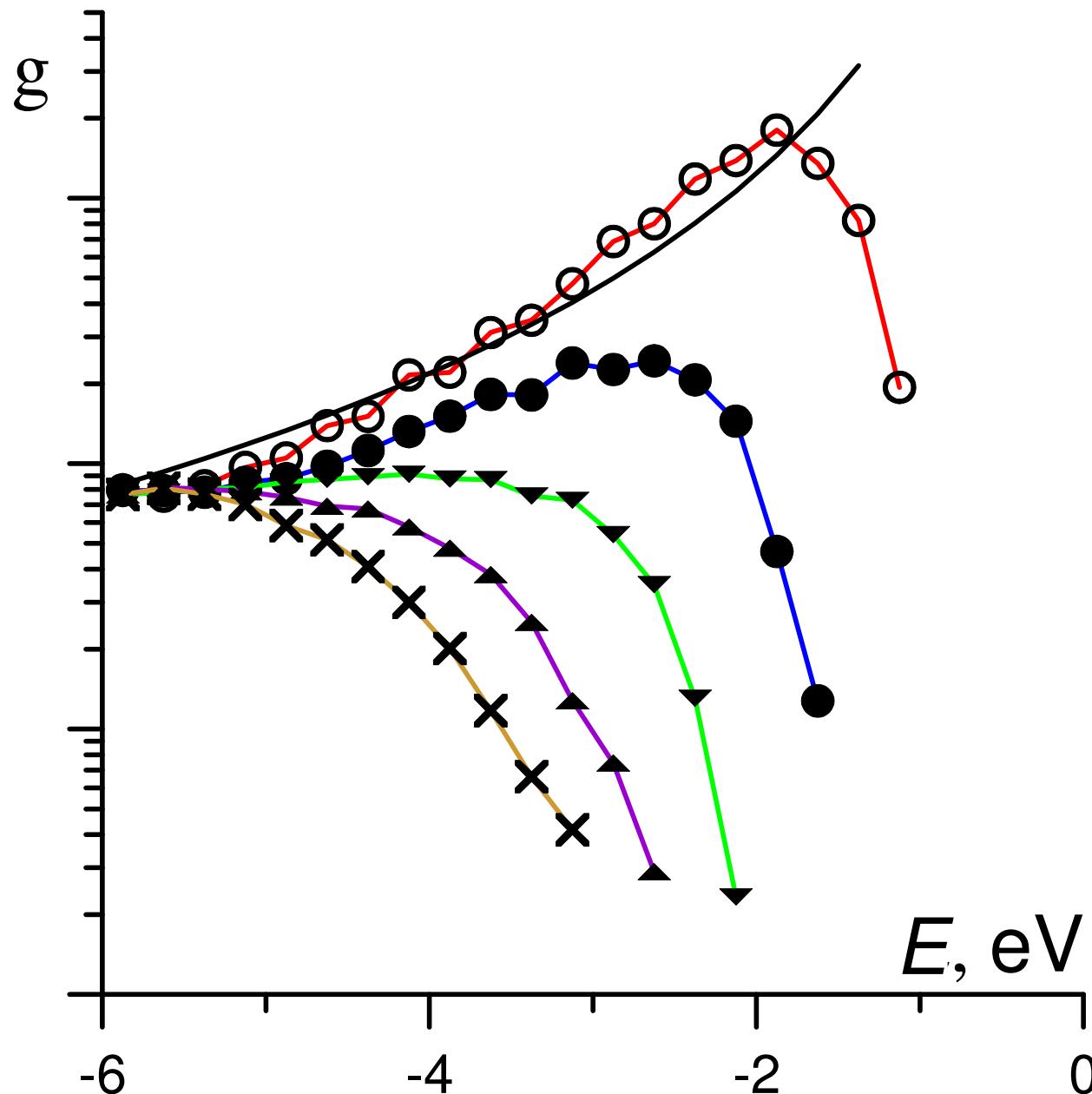
Dependence of ΔE on the density n_e



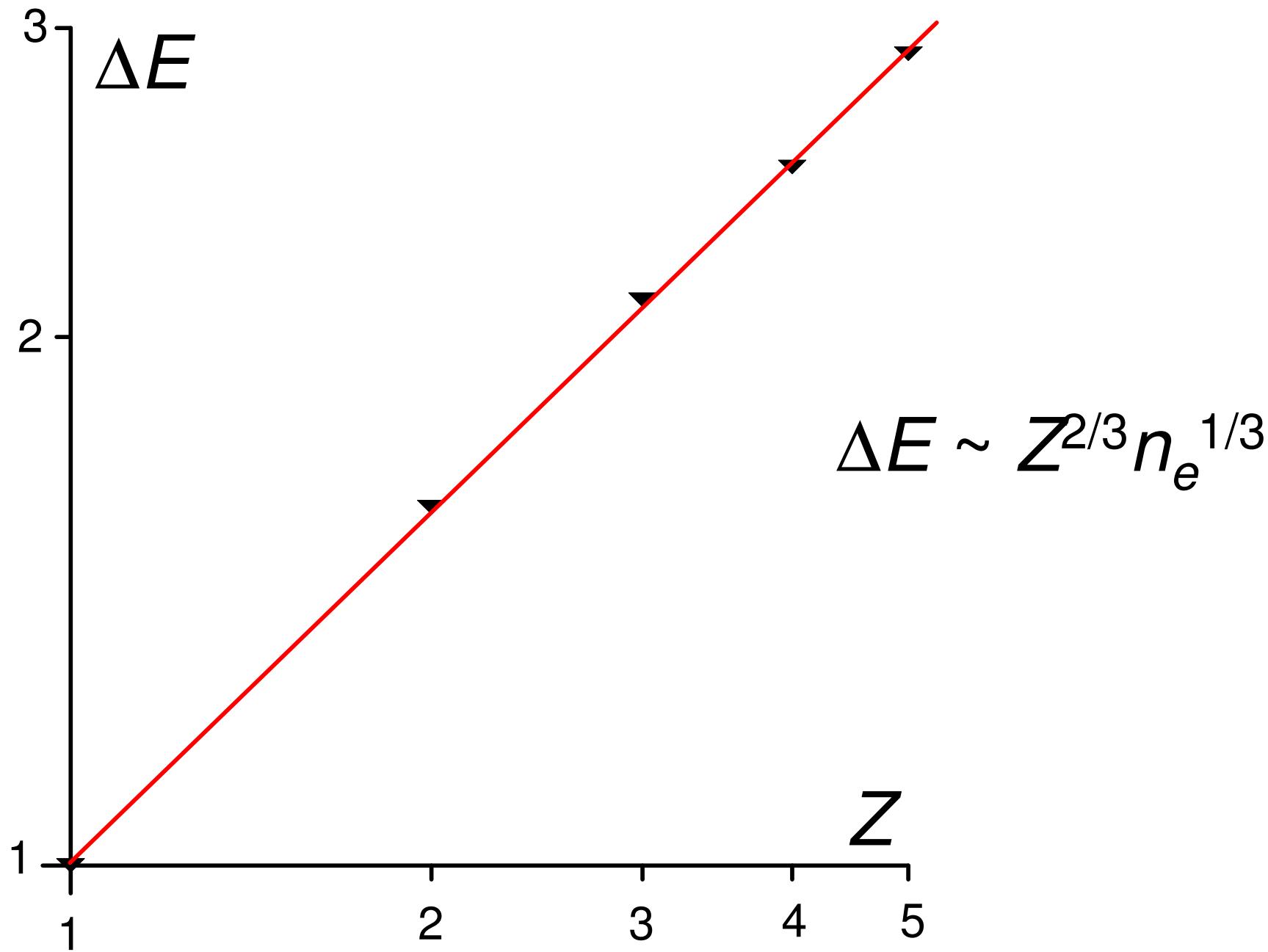
Density of electron-ion pair states at $n_e = 8 \cdot 10^{19} \text{ sm}^{-3}$ for different temperatures



Density of electron-ion pair states at $\Gamma = 0.5$
for different ion charges $Z = 1, 2, 3, 4, 5.$

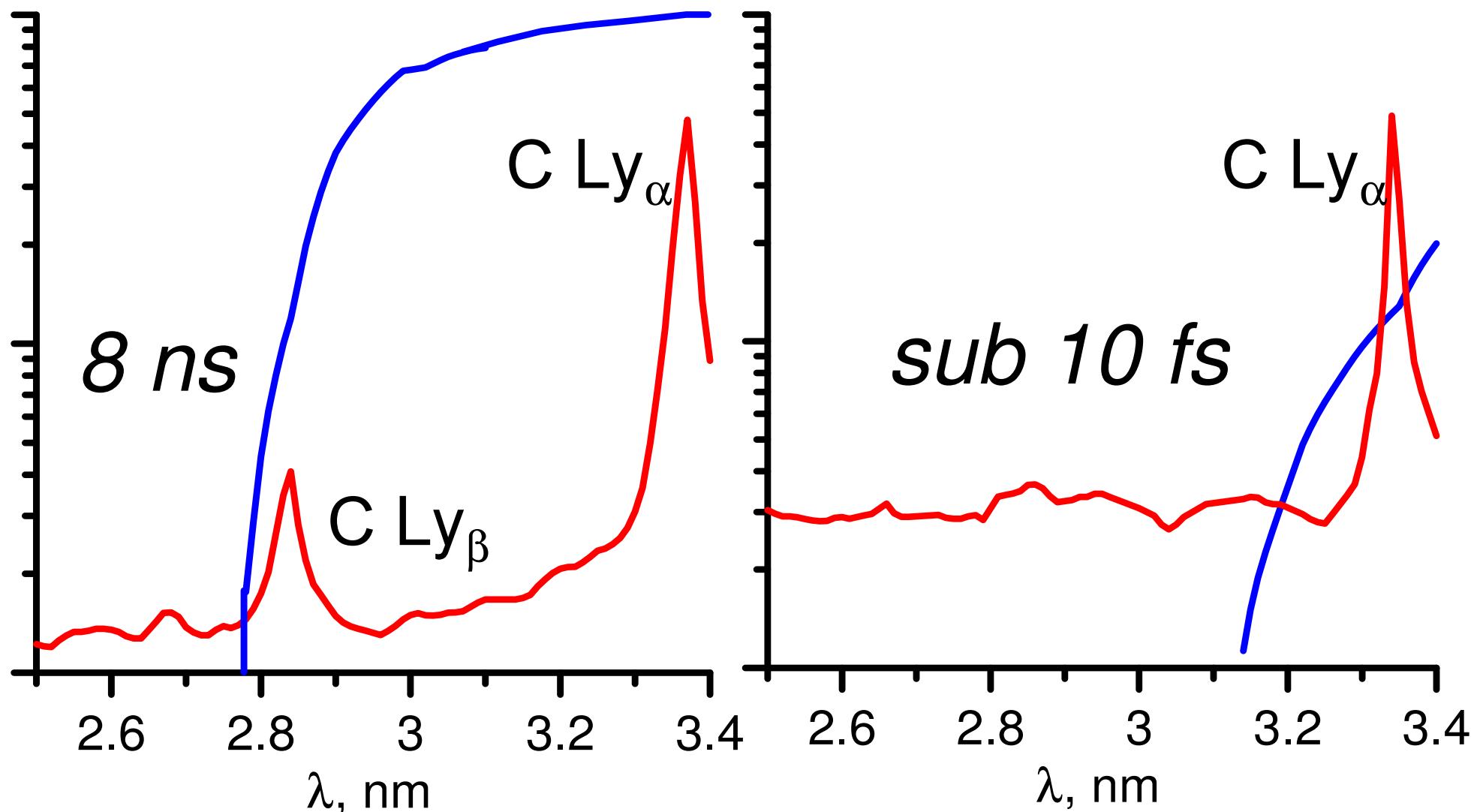


Energy dependence of ΔE on density and Z



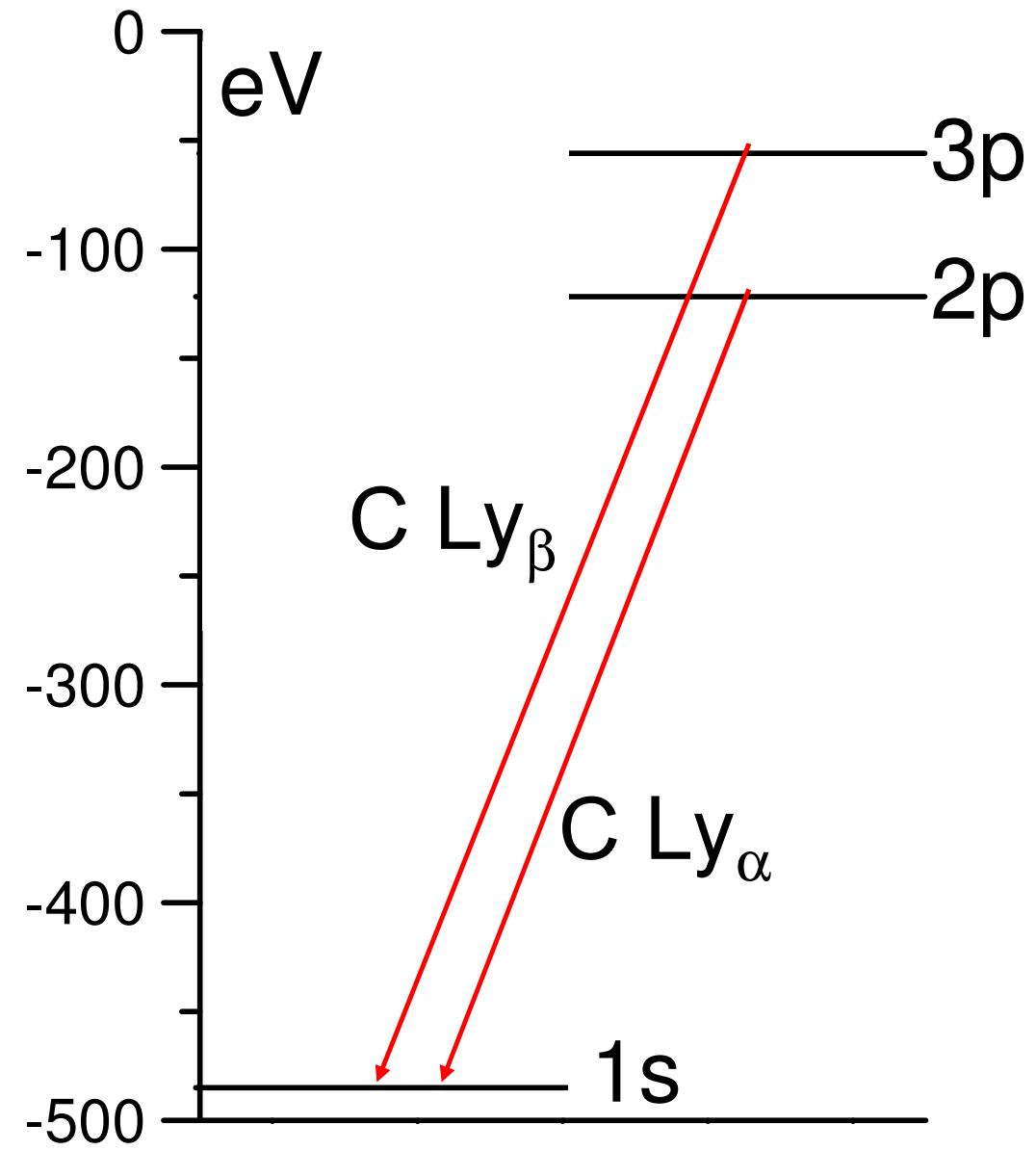
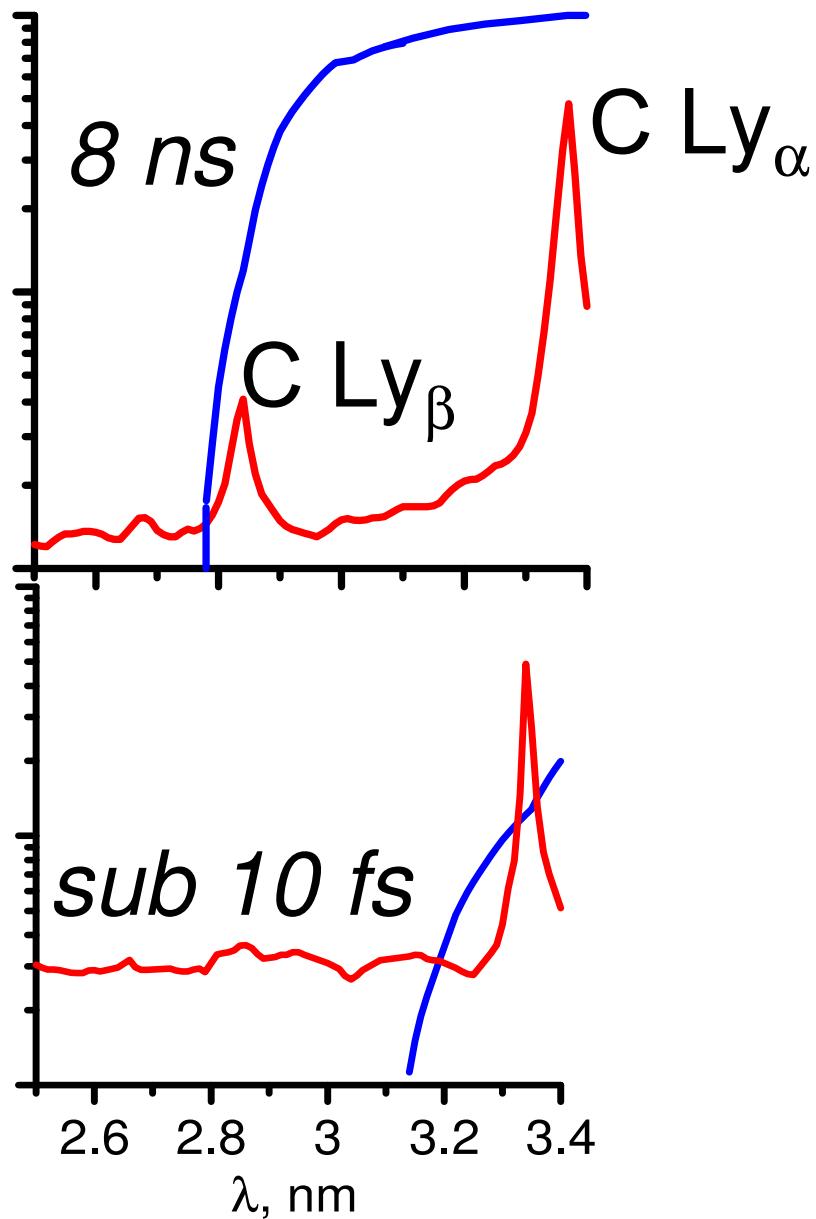
2.6. Disappearance of spectral lines

Density of electron-ion
pair states
for MD model

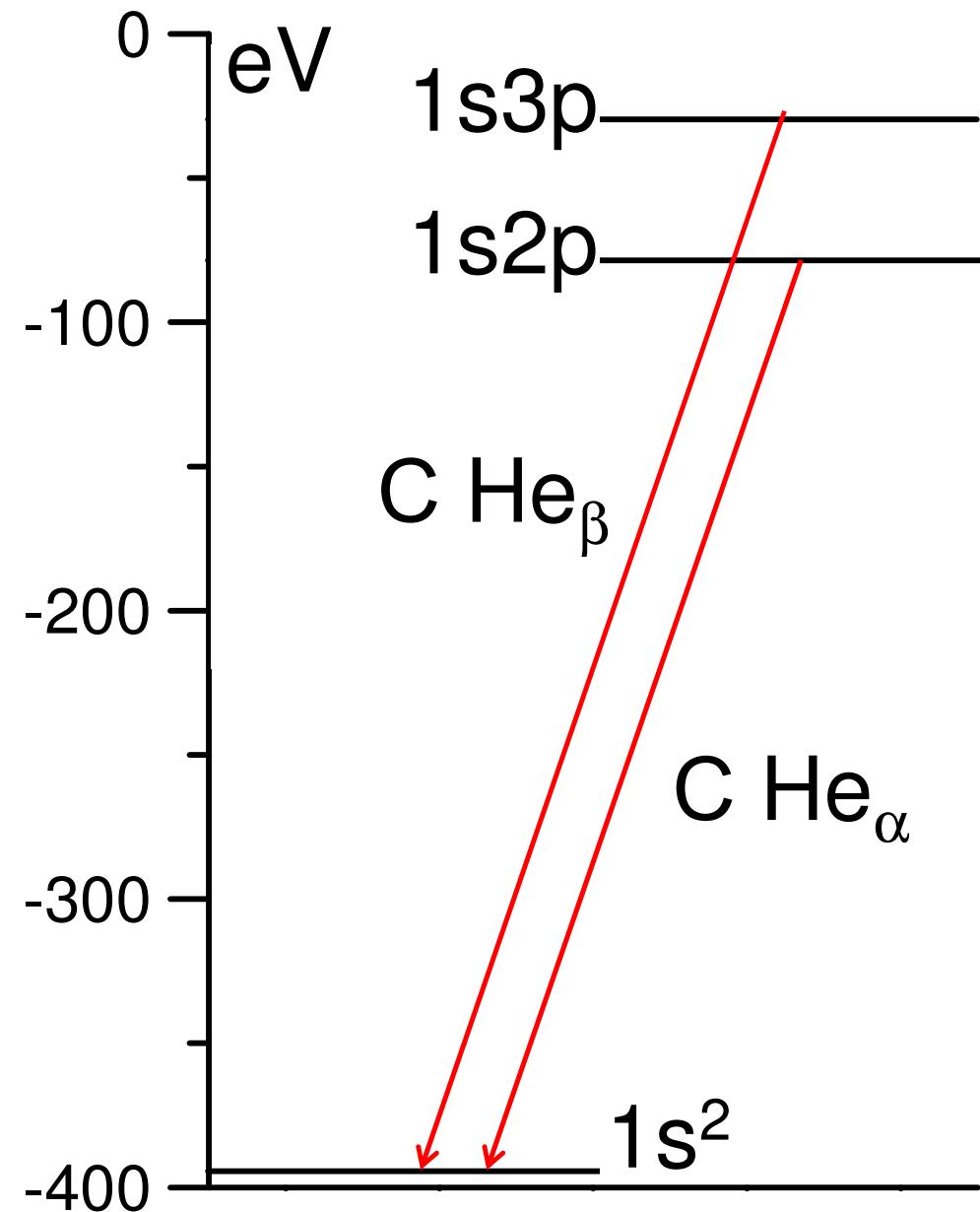
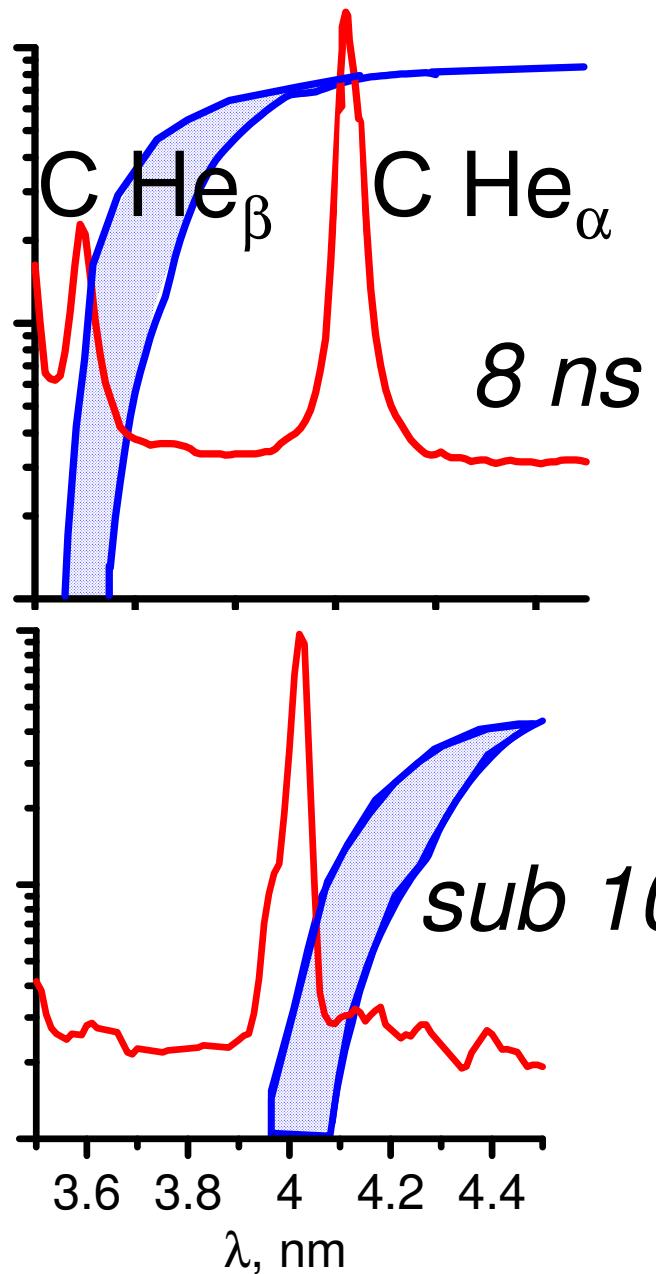


Plasma X-ray spectrum at
8ns and sub10fs laser impulses
J.Osterholz, F.Brandl, T.Fischer, D.Hemmers,
M.Cerchez, G. Pretzler,O. Willi, S. J. Rose,
Phys. Rev. Letters **96**, 085002 (4pp) (2006)

Plasma X-ray spectrum at 8ns and sub10fs laser impulses



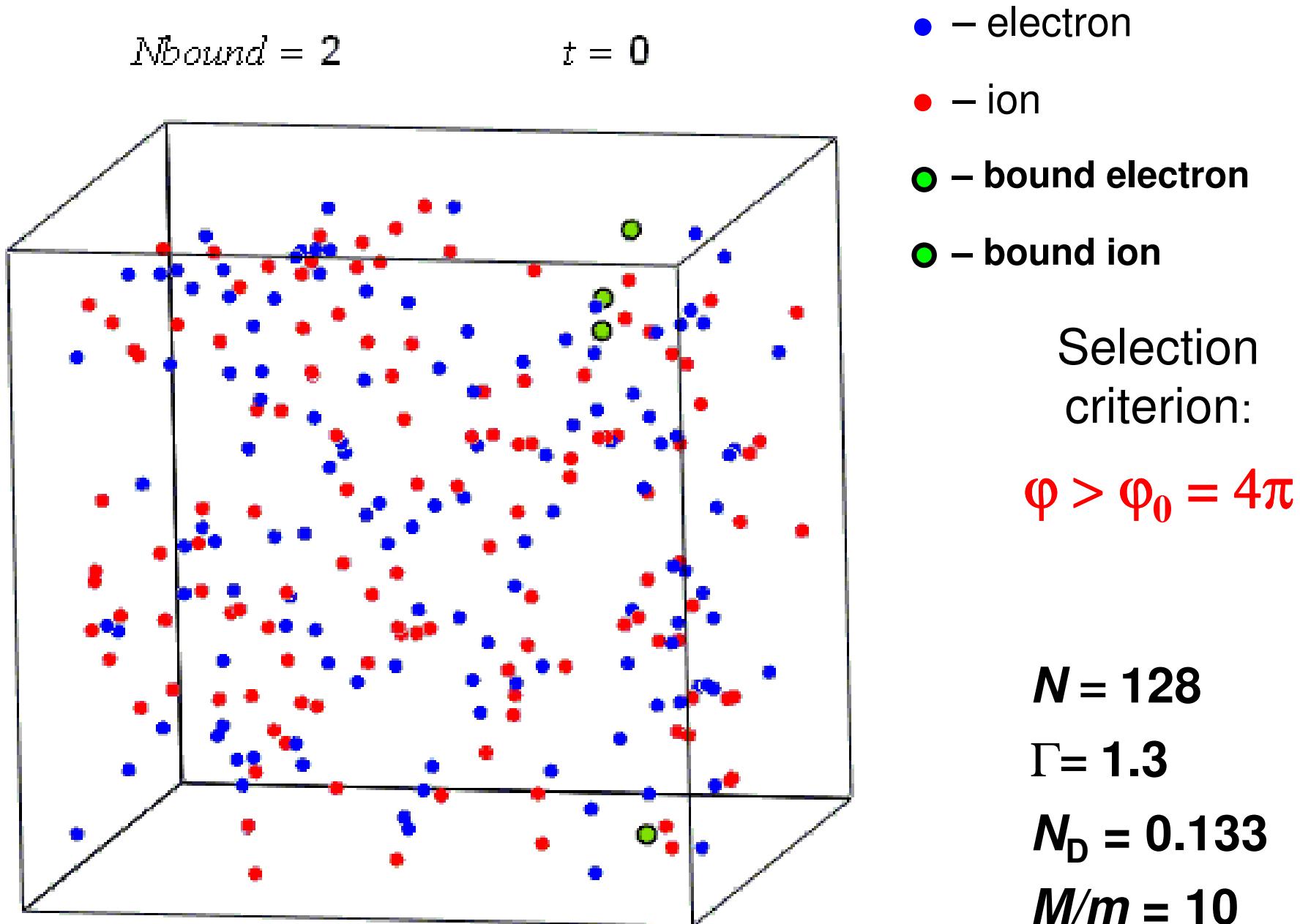
Plasma X-ray spectrum at 8ns and sub10fs laser impulses



3. Nonideality effects

Collisional recombination

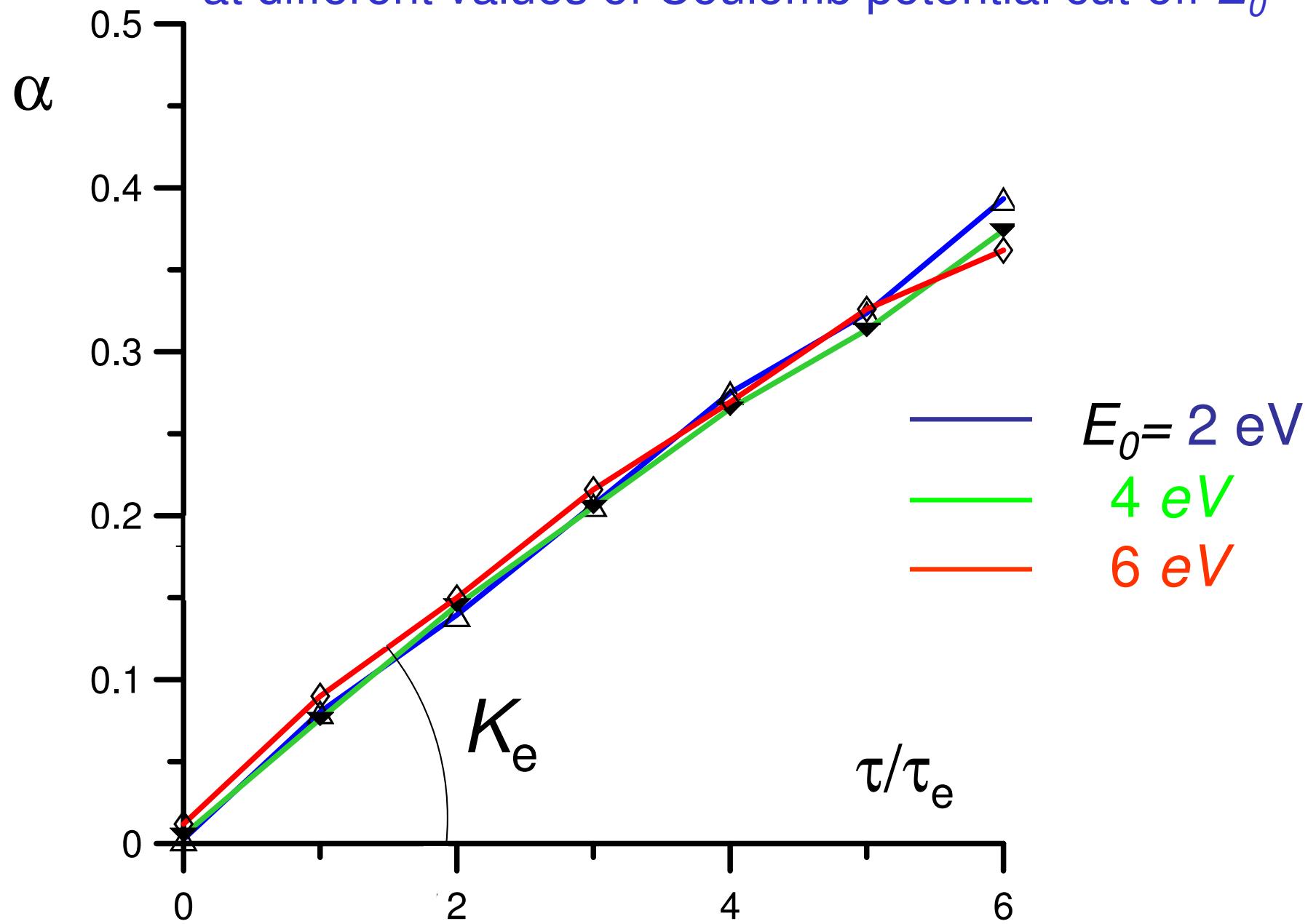
Pair transient bound state visualization



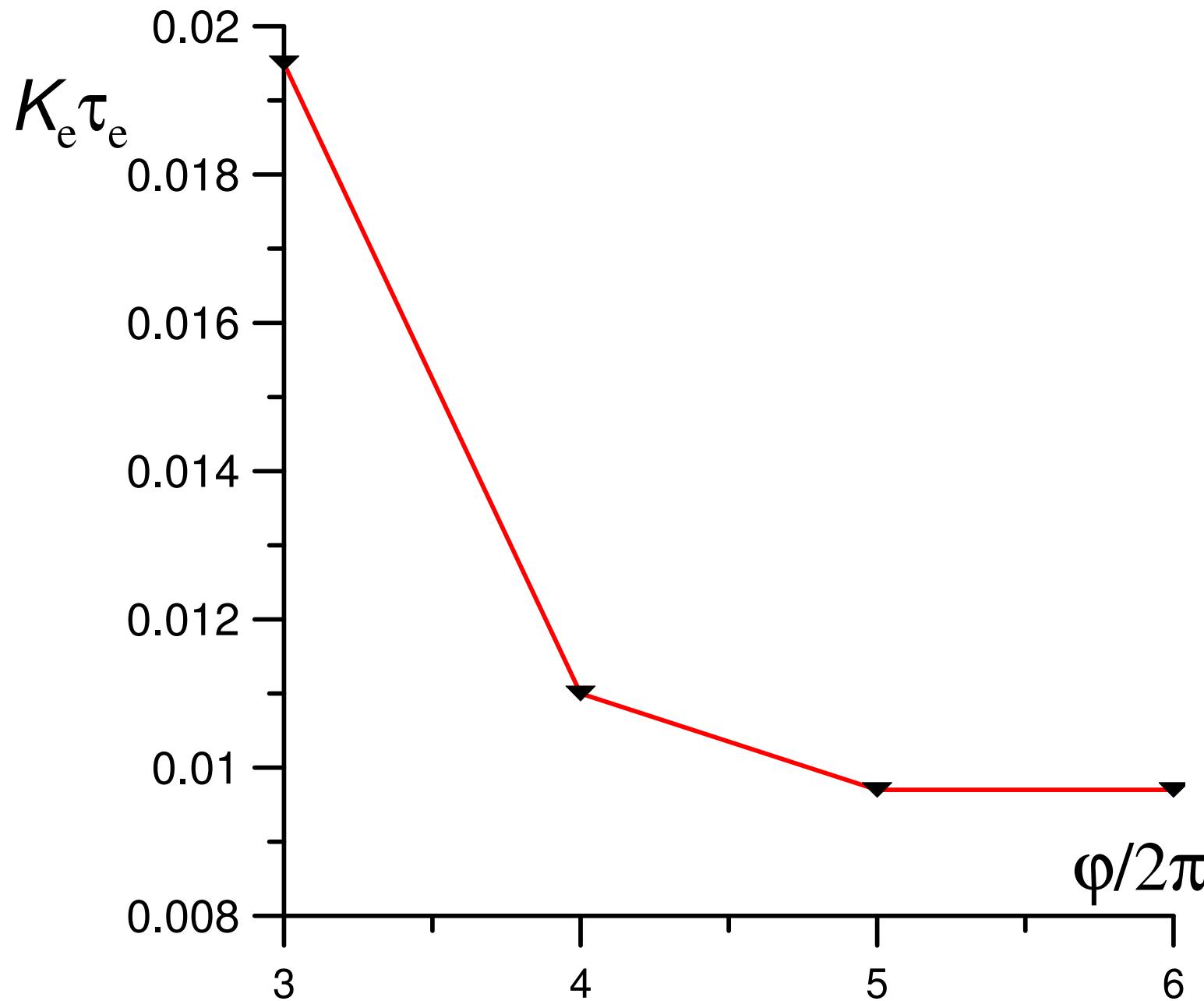
Algorithm idea

1. An initial state *without pairs* is created.
2. The initial rate of the pair appearance is defined.

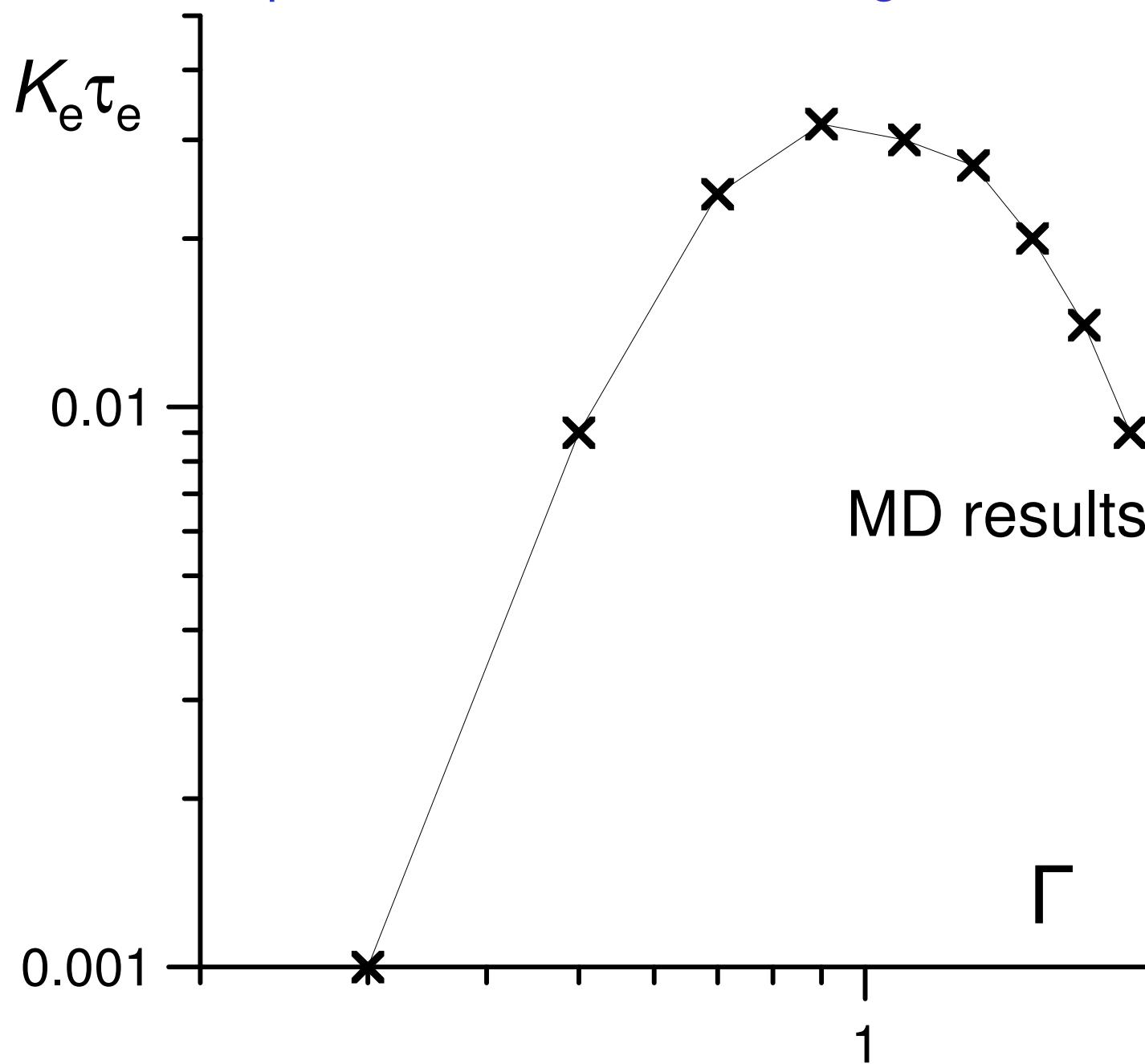
Dependence of the pair fraction α on time
at different values of Coulomb potential cut-off E_0



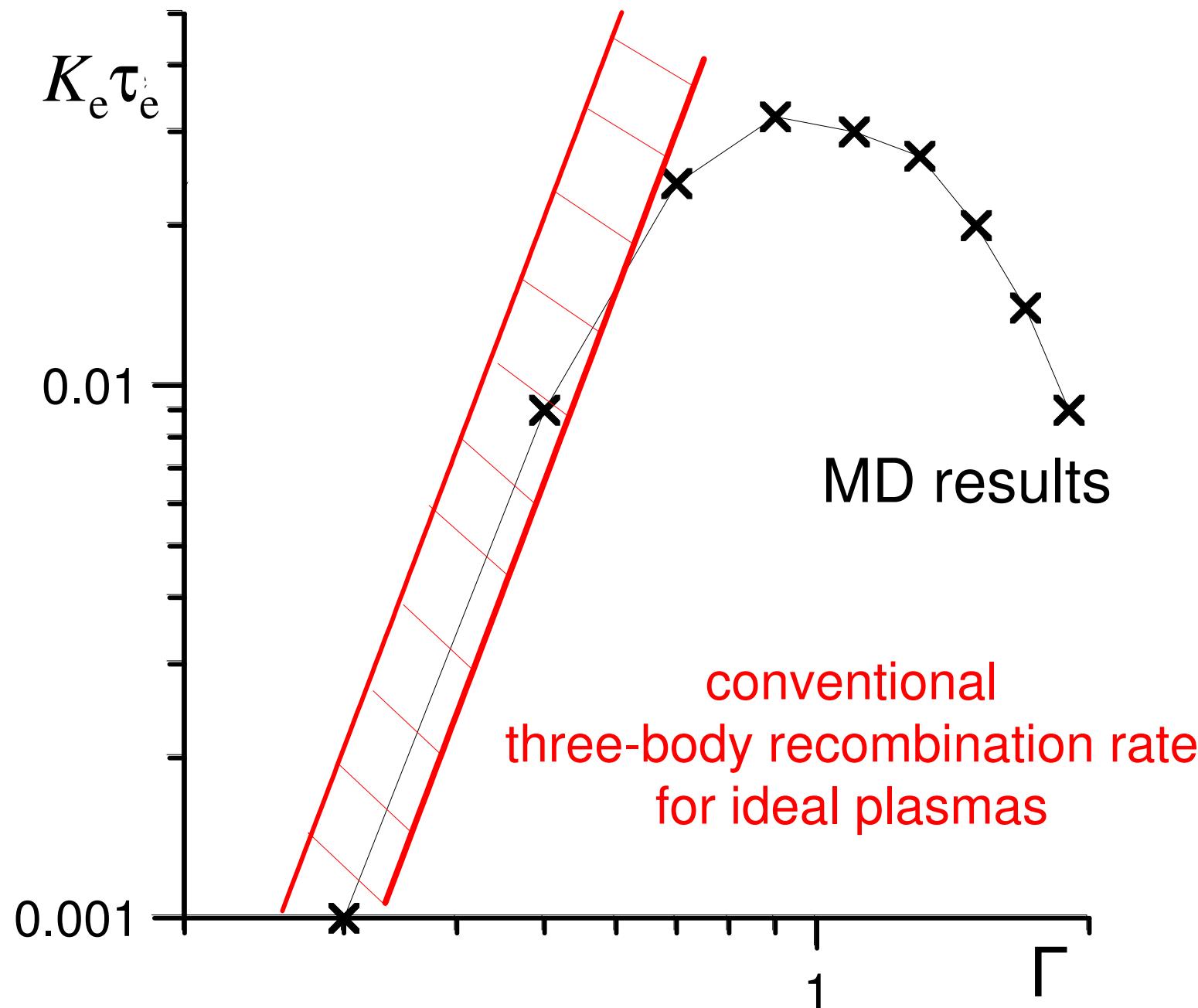
Recombination rate dependence on phase



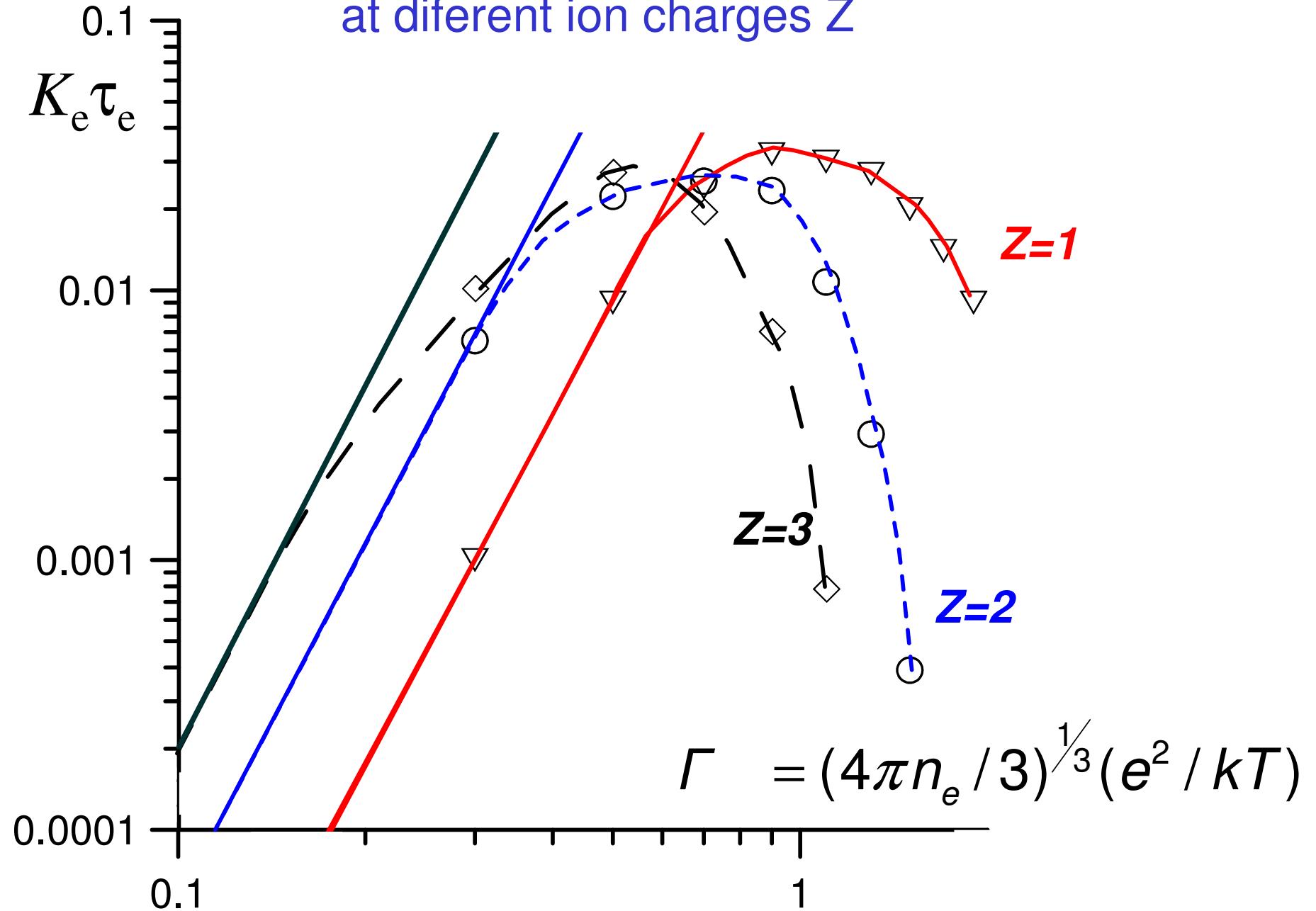
Dependence of recombination rate on the nonideality parameter at the ion charge Z = 1



Dependence of collisional recombination rate
on the nonideality parameter at the ion charge $Z = 1$

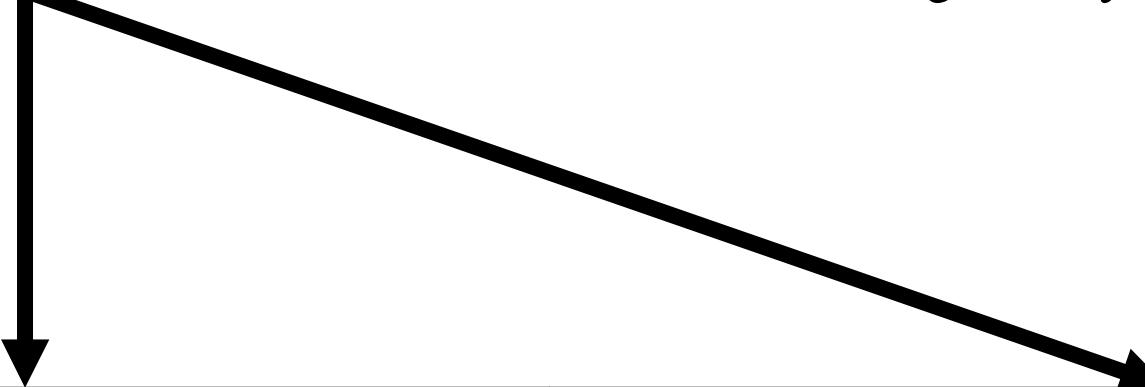


Dependence of recombination rate on the nonideality parameter at different ion charges Z



Recombination rate

$$K_e = C \cdot Z^3 e^{10} m^{-1/2} \cdot n_e^2 n_i T^{-9/2}$$



Ideal plasmas

$$C = 1.4$$

Strongly coupled plasmas

$$C = C(\Gamma, Z)$$

Approximate formula

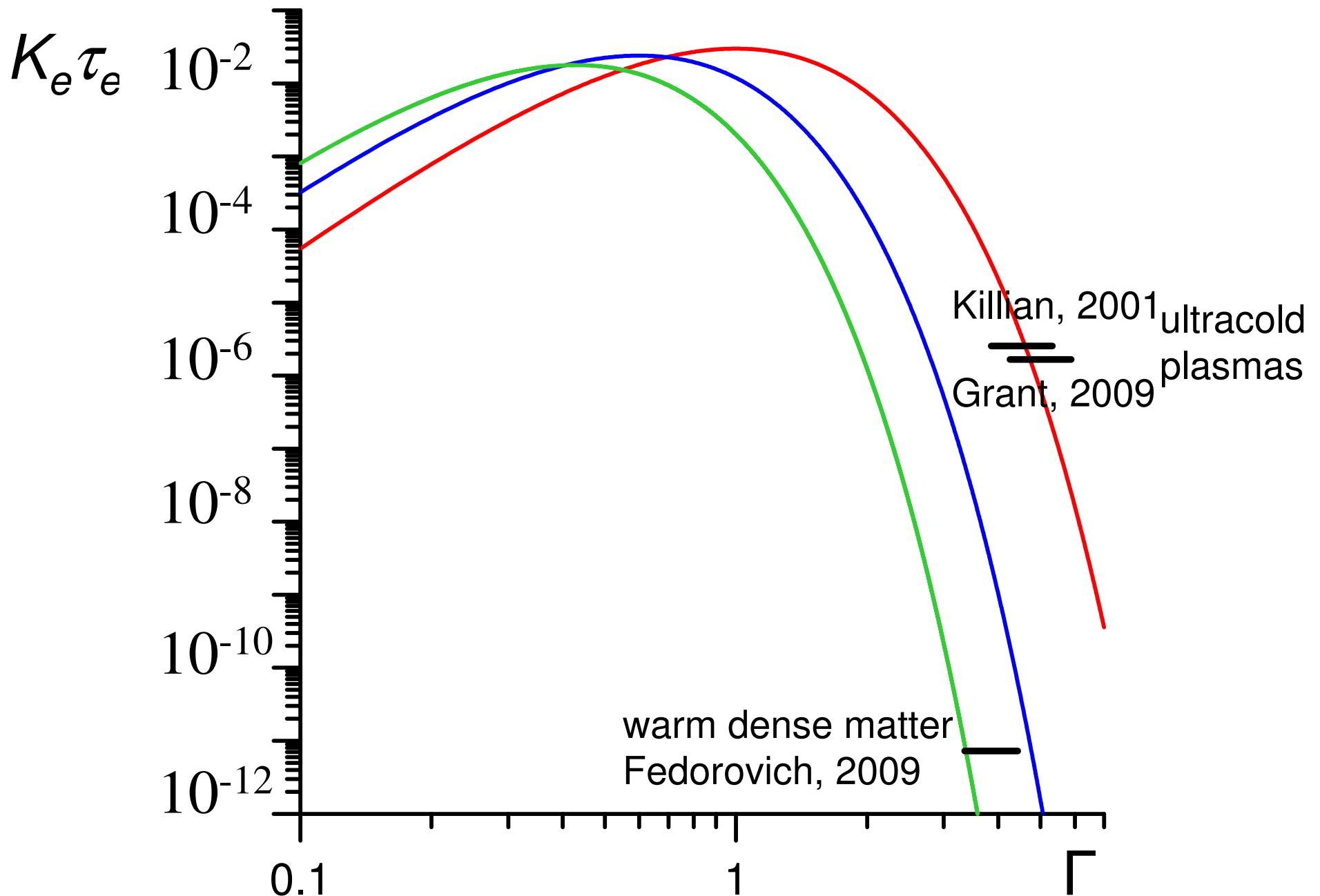
$$K_e \tau_e = K_0 Z^3 \Gamma^{9/2} e^{-\lambda_0 \Gamma} e^{-\lambda_1 Z \Gamma}$$

$$K_0 = 2.7$$

$$\lambda_0 = 1.5$$

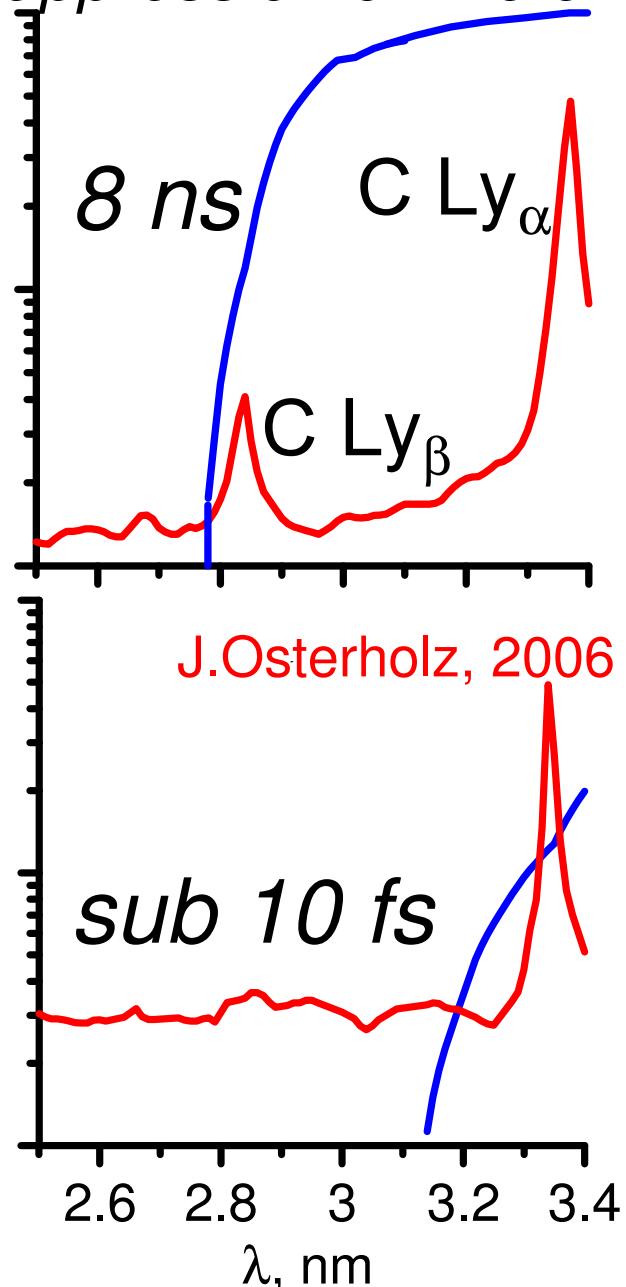
$$\lambda_1 = 3$$

Comparison to experimental data



Density effect:

suppression of line emission



Conclusions

Nonideality effect:

suppression of recombination

